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THE MAGIC OF CHEMISTRY

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HEAT, COMBUSTION, AND OXYGEN

1. How do alchemy and chemistry differ?
2. What was the philosopher's stone?
3. How is a match adapted to its purpose?
4. Which heat reactions spread slowly?
5. What is touch-paper?
6. How is gunpowder made?
7. Why does gunpowder explode? What is the explosion?
8. What was Greek fire?
9. What was the earliest use of gunpowder?
10. How is oxygen supplied in fireworks?
11. How are coloured fires made?
12. What is a quick-match?
13. How is charcoal made? What was the chief purpose of making charcoal?
14. How is quicklime made?
15. What materials are used in smelting iron? What is the purpose of each?
16. Why do heat and pressure usually increase chemical reaction?
17. What is the effect of extreme cold on chemical reaction?

THE alchemist of old was a man to reckon with. He held himself aloof from the common run of men, in grim experimental gloom. He surrounded himself with mysteries. His apparatus was strange. He had alembics of fantastic form that he used for distilling; and jars and bottles of equally fantastic form that held potions and essences. He expressed his discoveries and speculations in strange, outlandish symbols, and sometimes in anagrams. The decorations of his laboratory were the dried skins of crocodiles, and creatures of the slimy half-world between land and water. It is little wonder that the alchemist was credited with dealings in black magic, and that people whispered of familiar spirits. At any moment he might discover the secret of perpetual youth, the elixir of life. At any moment he might find the recipe for the philosopher's stone, the combination of materials that would transmute the baser metals into coveted gold. And so men who caught furtive glimpses of him, saw in him the possibility of boundless wealth, and the power that went with it. Many of the alchemists were charlatans, trading on the credulity of the ignorant and selling them dross as gold; 'alchemist's gold' had a bad name. But many of them were genuine seekers after chemical knowledge, carrying out genuine chemical experiments.

And have we changed so very much?

We have certainly changed some of the names. The alchemist has dropped the 'al', which after all is only the Arabic for 'the', and become a chemist. The alembic we now call a retort, or distilling apparatus. But the chemist still has about him an air of inscrutable mystery to the non-scientific. We still talk of chemical magic. The twisted tubes of the modern chemist are even more elaborate and fantastic than those of the alchemist. Chemists still use symbols that are weird and outlandish to those who do not try to understand them. The quest for perpetual youth still goes on; some seek it in sour milk, and some look for it in monkey glands. There is even a report that horse serum was used in an endeavour to confer quasi-immortality on Stalin. Transmutation

into gold has actually been achieved, even if only on a minute scale. The modern chemist can be just as secretive about his results and discoveries as ever an alchemist was. He may be hiding them from the prying eyes of trade rivals, or from foreign spies. And there are branches of the chemist's trade where charlatanry is not unknown.

Nevertheless, there is a great difference between the alchemy of old and the chemistry of today, especially in the general level of honesty. Most of the results of research are published openly for all who are interested to read them; they are not hidden in anagrams and cryptograms. Methods are more exact, and more open to criticism. There is little that is secret about 'the tricks of the trade'. The chemist's methods are the established ones of heating, distilling, filtering, dissolving, together with the armoury of new methods that have been added by the present generation. And there is finally the great heritage of scientific knowledge that is open to all.

Lighting a Fire

First amongst chemical methods, now as of old, comes the application of heat. Heating is a bit of chemical magic that we all use every day, and that we hardly ever think about. We strike a match to light the fire, and we seldom realize what an admirable product of the chemist's art is in our fingers.

Every part of the match is adapted to its purpose. The head contains saltpetre or potassium chlorate to supply the oxygen needed for burning. It also contains sulphur, charcoal, or other substances that will burn readily. And in the head of the match, or on the prepared surface of the box, there is a little red phosphorus to start the flame. The match-stick is dipped in oil to make it more inflammable.

A match contains everything necessary for the chemical reactions of burning. The one other thing necessary is added heat. Many chemical reactions have to be started by heating the substances, but once the process has started it supplies its own heat to continue and spread the reaction.

Some reactions take place at room temperatures. Some require a slight rise of temperature, and some a much greater rise. Not all reactions give out heat, and so we may have to go on supplying heat to keep a reaction going. But the reactions of burning certainly do supply heat.

A match is very nicely formed to give the various degrees of heat needed to start the successive reactions. Red phosphorus requires a very small rise of temperature to cause it to burn. The necessary heat is supplied by friction between the head of the match and the prepared surface of the box. The next stage requires greater heat, and this is supplied by the burning phosphorus. The head flares up because there is a plentiful supply of oxygen from saltpetre or potassium chlorate. This flare-up supplies the still greater heat required to fire the match-stick. We apply the burning match to paper in the grate. The paper fires wood, and this in turn supplies the much higher temperature required to fire coal.

From stage to stage we thus find each reaction supplying heat to start off a more difficult reaction.

Slow-spreading Reactions

Some of the reactions which supply their own heat spread quite slowly, as if there is just enough heat to keep them going.

Here is an experiment which illustrates the slow spread of a chemical reaction. We mix iron filings with flowers of sulphur—a little more than half as much sulphur as iron, say four parts by weight of sulphur to seven parts of iron. We fill a test-tube about two-thirds full with this mixture. We heat the mixture carefully in a rather low Bunsen flame; we hold the tube so that the flame is well down at the bottom of it. After a short time a glow starts at the bottom of the tube. The reaction has begun, and there is no need for further heating; the reaction provides all the heat that is necessary. The glow spreads slowly upwards through the mixture of sulphur and iron. We are left with a grey-black substance which is neither

sulphur nor iron, but a compound called ferrous sulphide. The compound does not burn as sulphur does, and it is not attracted by a magnet, as with iron.

Here is another very simple experiment in the slow spread of a heat reaction. We make a strong solution of saltpetre by dissolving as much as possible in lukewarm water. We soak a piece of very thin paper in the solution, and let it dry thoroughly. The water evaporates, and leaves dry saltpetre on the paper. We make a tight roll of the paper, and put a glowing match to one end of it. The paper sputters and smoulders, and the glow of chemical reaction passes slowly along it.

The touch-paper used in setting off fireworks has been soaked in saltpetre solution. The slow spread of the reaction through the touch-paper gives us ample time to get well out of the way before the really fierce reactions of the firework start. The touch-paper is a very necessary safety device.

Villains of old, when they wanted to blow up a ship, as they often did in the tales that enlivened my boyhood, made a fuse by soaking a length of rope in saltpetre solution, or by rubbing damp gunpowder into it. The slow spread of chemical reaction between the oxygen of the saltpetre or gunpowder and the material of the rope, gave them time to take to the boats and row off to a safe distance before a spark reached the open keg of powder at the end of the fuse.



FIG. 1

We have all sung about the British Grenadiers, how 'Our leaders marched with fuses, and we with hand grenades'. The short fuses of the grenades were lighted from the main fuses carried by the leaders. They were nicely timed, so that they could be flung into the midst of the enemy and leave them no time to remove the fuses. Before a naval battle of olden days the fuses were blown upon till they were burning well. These fuses were used to touch off the cannon. But let us leave villainy and war, and turn to something less harmful.

A Chemical Picture

Here is a sort of chemical picture that can be drawn with the aid of a strong saltpetre solution, and a slow-moving chemical reaction. We want very thin paper for the picture, and paper with very little glaze, so that it will absorb the solution. We use a small paint-brush to draw the picture. We dip it in the solution and draw the picture with fairly thick lines. There are two things to watch in drawing the lines. The lines should be continuous, and they should not entirely enclose small sections of the paper.

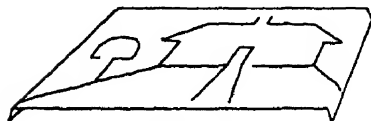
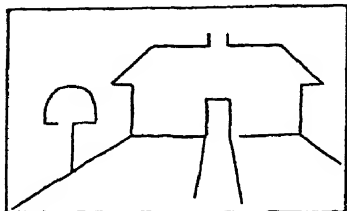


FIG. 2

dry the paper thoroughly. We turn down the edges of the paper all round, so that it may stand up clear of the table on which it rests; the paper along the lines will burn more effectively if this is done. We touch the starting-point with the tip of a glowing match. If all goes well, a glow spreads slowly along the lines, and draws the picture.

Gunpowder

Not by any means all chemical reactions spread as slowly as the ones we have examined. Indeed, some of them spread with extreme rapidity. Gunpowder is prepared for just that purpose, that the chemical reactions of burning may spread through it rapidly. It is made of three substances: saltpetre or potassium chlorate to supply the oxygen for fierce burning, and sulphur and charcoal to burn. A usual mixture is: saltpetre, 15 parts; charcoal, 3 parts; sulphur, 2 parts.

Here is a word of caution about powdering substances: always powder them separately, and never when they are mixed. We can powder saltpetre, charcoal, and sulphur

separately, and then mix them in the given proportions. It is best not to make too much of the mixture at once, say: saltpetre, $1\frac{1}{4}$ ounces; charcoal, $\frac{1}{4}$ ounce; sulphur, $\frac{1}{8}$ ounce, or rather less than $\frac{1}{4}$ ounce.

This mixture burns well, but it does not flash off like gunpowder. For gunpowder the materials are very carefully chosen, and very finely powdered. The best charcoal is made from dogwood, willow, or alder. The sulphur used is powdered brimstone, not flowers of sulphur. The finely powdered materials are very thoroughly mixed, damped, compressed, dried, broken into grains, dusted, and glazed. All those processes are necessary to produce a powder that will flash off rapidly. The much slower-burning gunpowder mixture is far better for experiments than gunpowder which flashes off too rapidly.

We spread a narrow line of the gunpowder mixture, and see that there are no gaps left in it. We put a match to the end of the train, keeping the body well out of the way. The mixture flares up, and the flame moves slowly along, but much more quickly than the glow which passes through touch-paper.

When there is a mass of gunpowder, not loose grains spread in an open line but a tightly packed mass, a reaction, which may be started by a spark, spreads through the whole mass of powder with extreme rapidity. The saltpetre supplies ample oxygen to burn all the charcoal and sulphur, and so the powder goes off in a flash. In that flash a great mass of highly heated gases is produced. The chief of these gases are: nitrogen, produced by the saltpetre, which is potassium nitrate; carbon dioxide, produced by the burning charcoal; and sulphur dioxide, produced by the burning sulphur. The temperature may go up as high as $2,000^{\circ}\text{C.}$, and the pressure of the heated gases may be as high as 40 tons to the square inch. That enormous pressure is the explosion. The accompanying glare comes from white-hot gas produced in the explosion.

Greek Fire

Chemical warfare is no new thing; it goes far back into history. The Assyrians left among their surviving records

some which show that they used liquid fire against their enemies.

The most famous of all the inflammable projectiles was the Greek fire which was first used in the defence of Constantinople as long ago as A.D. 673. Sometimes the blazing mass was poured from cauldrons about the ears of attackers. Sometimes it was flung from catapults in barrels and other containers.

Greek fire was much used in sieges and in naval battles. It included pitchy material, so that it adhered where it struck. It gave off thick clouds of frightening smoke, and loud explosive noises. For these reasons it was often effective in reducing the enemy to panic. And it must have been effectively destructive when used against wooden ships.

The art of making Greek fire was a carefully cherished secret, though many of the ingredients could be guessed from their effects, and its composition is now fairly well known. It included bitumen, which would burn fiercely and give off clouds of thick smoke. It also included naphtha, which would burn readily and give the flames a good start. Roger Bacon says that it included, amongst other materials, saltpetre and sulphur, so that it had the essentials of gunpowder.

Fireworks Came First

Fireworks are sometimes regarded as a sort of by-product of the explosives industry. It seems fairly certain, however, that the 'by'-product came long before the main industry. Gunpowder probably originated on the plains of India and China, where there is much saltpetre in the soil. It was the discovery that saltpetre promoted fierce burning that made it possible to have a gunpowder mixture. The very effective powder we have nowadays is quite a recent development. In earlier times the ingredients were mixed into a loose powder as they were wanted.

The earliest use of gunpowder seems to have been in the making of crackers, the crackers for which the Chinese

have long been famous. Rockets were an easy development. We have only to fill a thin tube, closed at one end, with a rapidly burning mixture, to have a rudimentary rocket. A squib is a sort of small rocket without the balancing stick.

I practised a very early form of jet propulsion when I was a small boy. I used to attach squibs to the back of small boats, and set them off. The career of such a boat was lively and brilliant, even if it was brief and extremely erratic. It was only a matter of time before this rather obvious invention could be applied to aeroplanes, and even to space-ships.

When gunpowder first came to be used for warlike purposes, it was used in grenades with fuses. The Saracens hurled grenades from catapults at the Crusaders; these grenades often included other combustible materials. They appear to have had an effect on morale out of all proportion to the material damage they did.

Modern Fireworks

The fireworks we have now are elegant productions of the chemist's art. The processes and methods used are adaptations of simple ideas. Their brilliance depends on the careful choice of materials, the careful preparation of these materials, and upon exact adjustments, as well as on ingenuity in producing novel effects.

We use chlorates and nitrates to supply oxygen for rapid burning; the most common of these are saltpetre, which is potassium nitrate, and potassium chlorate. The most common combustible materials are charcoal and sulphur; but powdered shellac, sugar, starch, resin, and other substances are used for particular purposes.

The proportions of the ingredients are carefully worked out so that the best results are obtained. If we want explosive burning we add more of the substances which supply oxygen, we powder everything very finely, we mix the materials thoroughly, and we compress them. For slower burning we use less of the materials which supply oxygen, and we powder and mix them less thoroughly.

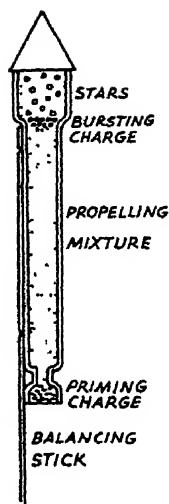


FIG. 3

Thus, the head of a rocket may contain a bursting charge of coarse gunpowder. The shaft of the rocket may be filled with a mixture like gunpowder, but slow-burning. And finally there is a priming charge of fine gunpowder (meal powder) to give the series of reactions a good start.

Iron and steel filings are sometimes put into the mixtures; they become white-hot as they are flung out, and they give brilliant, sparkling effects. Other metals are also used, either in the form of filings or as powders. Magnesium, zinc, antimony, copper—each has its own distinctive effect. Antimony, for example, is especially white and brilliant.

Fires are coloured by adding salts of various metals to the mixtures. Sodium gives a bright yellow light; we can get this colour quite easily by dipping a wire or a piece of brick in a solution of common salt (which is chiefly sodium chloride), and holding it in the blue flame of a gas-ring. Barium gives green, copper gives green or blue, calcium gives brick-red, and strontium gives crimson light. By using chlorates or nitrates of the various metals we kill two birds with one stone: we add colour to the flame, and we also supply it with oxygen to keep it burning fiercely.

When we want a lot of fireworks to go off together we join them with a quick-match. As the name implies, this burns very quickly. It is made by soaking cotton-wick in a paste of gunpowder, and drying it. Rotating fireworks are usually made to rotate about a pin or nail. Large ones are wooden wheels with squib-like fireworks fixed round the circumference. The stars of Roman candles and rockets are coloured-fire mixtures, made into a paste, and dried. They are driven upward or outward by means of charges of gunpowder.

Charcoal

The manufacture of charcoal is interesting as being a heat reaction which is purposely not completed. It is a very ancient process, and the ancient method is still followed in countries where there are ample forests. Billets of wood are made into piles 8 or 10 feet high, with the billets up on end. The pile is covered with turf, or some other non-burning material. It is then fired at the top. Heat spreads slowly downwards and water and volatile materials are given off as smoke. Holes are made farther down in the pile to admit air at a lower level, and smoke pours out from these. When smoking ceases the holes are carefully plugged up to prevent more air entering,

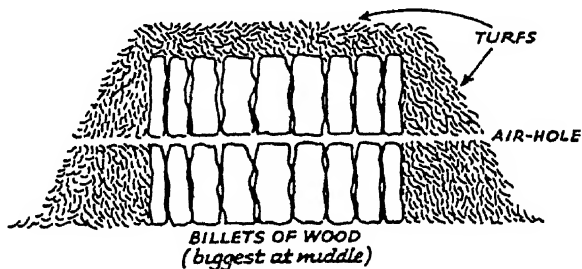


FIG. 4

and holes still lower down are opened. Finally, the heap, with all holes closed, is left to cool for two or three days. The charcoal can then be taken out.

The carbon burns less readily than the volatile materials; that is why it is left unburnt at the end. If more air were admitted the carbon would burn, and so change to carbon dioxide. We should be left with a small residue of mineral ash, and no charcoal.

Charcoal is a useful fuel for some purposes because it burns much more slowly than wood, and little heat is wasted in evaporating water.

Lime Burning

The process by which limestone is broken up into quicklime and carbon dioxide is one which requires heat not

merely to start it off, but to keep it going whilst the reaction proceeds. The reaction does not supply its own heat. That is to say, we cannot start it off and then leave it to its own devices.

Limestone, or chalk, which is a softer form of limestone, is baked in lime-kilns. Alternate layers of limestone and coal are put into the kiln, and the coal is fired. It raises the limestone to a cherry-red heat (900°C.). At this temperature the limestone splits up into the white solid called quicklime and the invisible gas, carbon dioxide. The hot gas pours out and disperses into the atmosphere.

The kiln is left to cool, and the quicklime can then be taken out. It is a compound of calcium and oxygen—calcium oxide.

We take a piece of cold quicklime, and pour a little water on it. The water sinks in rapidly, the lime becomes hot, and begins to steam; this reaction does give out heat. If we carefully adjust the amount of water we can have the lime as a powder. This slaked lime is not wet, unless we have poured on too much water. It is therefore not just damp lime. It is a chemical compound of quicklime and water.

Slaked lime is the stuff gardeners and farmers put on the soil as a fertilizer. Most plants flourish when there is lime or chalk in the soil. But there are some plants that soon die out in chalky soil. Rhododendrons, azaleas, and autumn-flowering heathers are examples. Winter-flowering heathers, however, do very well in limy soil.

Iron Smelting

Perhaps the most important of all the heat reactions used by man are those by which iron is obtained from its ores. The method goes far back into prehistoric times. Somewhere about 1000 B.C. men began to use iron, and with the coming of the Iron Age came one of the great steps forward in the development and civilization of man. Iron is still produced by the ancient methods in some parts of the world, and there are peoples who still have no iron. Indeed, great cultural development has been achieved by peoples completely without iron. The fine carvings for

which some of the Pacific peoples are famous were made without the use of metals of any kind.

Nevertheless, iron is the backbone of our civilization.

The iron ores are compounds of iron. Magnetite or magnetic iron ore, is an oxide of iron; it is strongly magnetic, and was the original lodestone used in compasses. Haematite is another oxide of iron which forms a red powder. Limonite is a hydrated oxide; it is haematite combined with water; it is also called brown haematite because of its colour. Spathic iron ore, or siderite, is carbonate of iron (ferrous oxide, the lowest oxide of iron, plus carbon dioxide). Iron pyrites, or iron sulphide, is an inferior ore.

In order to get iron from the oxides or carbonate we have to make them give up oxygen. They do this when they are very strongly heated by means of wood, charcoal, or coal. This is another reaction that does not supply its own heat: we have to keep up the supply of fuel.

It is commonly thought that the first iron used may have been meteoric iron, which is already pure enough for use. The actual smelting of iron ore may have come about accidentally, when a fire was made over lumps of the ore. The primitive method was an easy development from such an accidental occurrence. Lumps of iron ore were piled up with wood. The wood was fired, and the fire was kept blazing. To make it burn more fiercely a goat skin would be used as a bellows to drive a stream of air through it. After twelve hours or more of this treatment a spongy mass of iron was obtained. This could be beaten into the useful kind of iron called wrought iron.

The modern technique for getting iron from its ores has developed very gradually from the old method. There have been changes in the fuel used in smelting. Wood contains a lot of water, so it is not very good for the purpose. Charcoal is better because most of the water is driven out in preparing it. The old charcoal-burners were preparing charcoal chiefly for the iron smelters. Sussex was a great county for smelting. At the end of the sixteenth century, when the merchant adventurers of the first Queen Elizabeth's spacious days needed a great deal

of iron, the production of charcoal was so great that the forests were endangered, and the amount that was made had to be restricted. Then coal and coke began to be used. But the charcoal-burners objected so strenuously that their use was given up. Though coke had been known in the seventeenth century it was not until the eighteenth

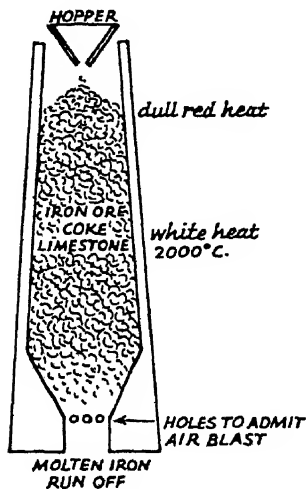


FIG. 5

century that its use became general. Coke is a better fuel than coal for iron smelting because it is harder. It does not crush so easily, and therefore furnaces burning coke can be built higher than would be possible if coal were used.

A tall blast furnace is, of course, more efficient than an open fire. All the materials are conserved in it, and the furnace can be kept burning continuously; it would be extremely wasteful to light the furnace afresh for each load of material. All that is necessary is to let it go out once a year, in order to clear away rubbish that has accumulated.

Where before simple bellows were used, blasts of hot air are now forced in at the foot of the furnace. This keeps the coke burning furiously. Near the top of the furnace there is a dull red heat, but near the bottom the materials are white-hot.

The raw materials, iron ore, coke, limestone, are dumped in at the top, and the furnace is thus fed continuously.

Series of Reactions

There is a series of chemical changes in the furnace. Carbon dioxide from the burning coke unites with more carbon to form carbon monoxide. The carbon monoxide is in close contact with the iron ore. In the intense heat it takes oxygen from the ore, and thus once more becomes carbon dioxide. The ore, by giving up its oxygen, has been reduced to free iron. In the hottest part of the fur-

nace, near the bottom, any remnant of ore that has so far eluded change gives up oxygen directly to the carbon of the coke.

The melting point of iron is something over $1,500^{\circ}\text{C}$. The temperature in the lower part of the furnace may be as high as $2,000^{\circ}\text{C}$. So the newly formed iron melts, and sinks to the bottom of the furnace. Every twelve hours the molten iron is allowed to run out into moulds made of sand. The sand has to be extremely dry; otherwise there would be dangerous explosions of steam. A more modern method is to allow the molten iron to run out continuously into the oblong blocks called *pigs*.

The limestone serves a very important purpose in the furnace. The iron ore contains various impurities, among them sand, sulphur, and phosphorus. The limestone unites with sandy matter to form a flux, or molten mass. The flux floats on the molten iron. It is run off separately, and carries with it most of the impurities.

The flux sets as slag, and the slag is not wasted. Some of the slag is used as a foundation for roads. Some of it, while still molten, has blasts of air driven through it. This drives the slag into threads which form a compact mass known as *slag wool*. The slag wool is a bad conductor of heat, and is used as a wrapping for hot pipes.

Heat and Pressure

Heat is often more effective in causing chemical change when it is accompanied by high pressure. The molecules of a gas are set wide apart in relation to their diminutive size. Clearly there cannot be a reaction unless the molecules come in contact with one another, that is, unless they collide. The molecules of a gas are in constant movement, so there are numerous collisions. When a reaction actually does take place the speed of reaction depends on the frequency with which collisions occur.

By heating a gas we increase the speed at which the molecules move about, and thus we increase the number of collisions per second, and so also the speed of reaction. With a very high temperature the increase in the number

of collisions may change a very slow reaction into a very swift one.

By compressing a gas we bring the molecules closer together. (Gases are easy to compress because the molecules are wide apart at atmospheric pressure.) A pressure of eight atmospheres would reduce the volume of a mass of gas to an eighth of what it is at atmospheric pressure. This would reduce the average distance between molecules to a half, 2 being the cube root of 8, and the number of collisions per second would thus be doubled. A pressure of a thousand atmospheres would decrease the average distance between molecules to a tenth, with a tenfold increase in the number of collisions.

Thus the number of collisions between molecules is increased in two ways, by high temperatures and high pressure. But there is more to it than that. The increased speed with which molecules move at high temperature increases the violence of the collisions. This may mean a great increase in the likelihood of reactions between the molecules. A reaction may occur which would not be possible with the comparatively mild collisions at a lower temperature. It may happen that a reaction proceeds so slowly as to be imperceptible. Such a reaction may be increased enormously by high temperature, especially when accompanied by high pressure.

At temperatures approaching absolute zero, we have the opposite state of affairs. The movement of the molecules goes down almost to zero. Collisions between molecules are few and feeble. In these conditions chemical reactions all but fade out. When they do occur they are extremely slow.

II

DISTILLING

1. What is distillation?
2. How is drinking-water obtained from the sea? And where?
3. Where does distillation occur in Nature?
4. How is sulphur refined?
5. How was sal-ammoniac prepared in Egypt?
6. What is the purpose of distilling with vacuum pans?
7. How is sugar prepared from beet?
8. What is fractional distillation?
9. How is absolute alcohol made?
10. How are brandy, rum, gin, and whisky made?
11. What is methylated spirit?
12. How is air distilled?
13. How is crude mineral oil distilled?
14. What is a bubble-cap?
15. Which are the usual fractions from distilled oil?
16. What is meant by cracking oil?
17. How is coal distilled?
18. Which are the two kinds of coke?
19. What products are obtained from coal-tar?

HEAT enables us to have many substances in each of the three forms, solid, liquid, and gas. Water may be solid ice, liquid water, or gaseous water vapour. Solid sulphur may readily be melted, and then boiled to a bright red gas. In each case we have the same substance chemically, in three different forms. It is the behaviour of the molecules that varies. In a solid the molecules have a very restricted range of movement. In a liquid the molecules slide about readily. In a gas they fly apart so as to fill the available space. Heat supplies the energy for the greater mobility of liquid molecules, and the still greater mobility of gaseous molecules.

We dissolve a little salt in water, and then heat the solution, perhaps in a large tin lid, over a gas-ring. The water evaporates, and the salt is left behind. If we take the trouble to weigh the salt before and after, we shall find the two weights nearly equal. There may be a little less salt left, because fragments of salt may jump out, unless we are very careful about heating. But the result should show that it is pure water that evaporates.

The reverse process is condensation of a gas into a liquid. We heat to evaporate; we cool to condense. When a kettle is boiling we may hold a cold plate in the escaping steam. The cold plate is quickly covered with condensed water.

Fresh Water from Salt Water

We can use a filter to clear water of suspended matter. But dissolved matter goes through the filter-paper. To get fresh water from salt water we need the double process:

- (i) We boil the salt water to change the water into steam.
- (ii) We cool the steam to condense it into liquid water.

Both steam and condensed water are pure water. The double process is distillation.

The diagram shows a simple distilling apparatus.

X is a vessel in which the impure water is boiled.

Y is a tube along which the steam passes.

Z is the condenser.

The tube which carries the steam through the condenser is sometimes coiled, so that there is a large surface for condensing. A stream of cold water runs in from below,

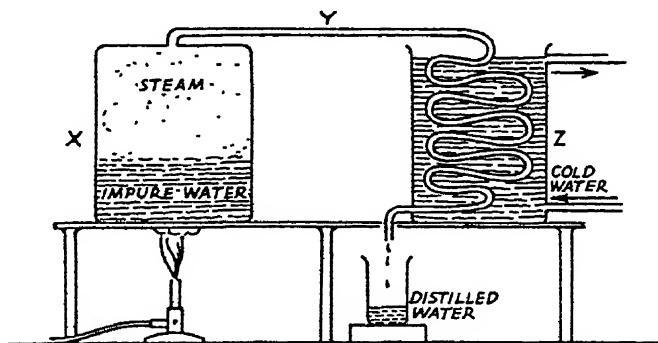


FIG. 6

and out at the top; this is to cool the condensing coil. The cooling water need not be pure, it does not come in contact with the steam or the condensed water. The condensed water runs out at the bottom of the coil into a jar.

The distilled water is unpalatable, because the air has been boiled out of it. We can render it palatable by shaking it up with air.

The crew of the Ancient Mariner's ship seem to have been unaware of this method of getting fresh water from salt water:

Water, water, everywhere,
Nor any drop to drink.

A knowledgeable and ingenious person could have rigged up a large kettle for boiling sea-water, and a condenser that could have been kept cold with sea-water. It is a pity there was no chemist on board.

Drinking-water from the Sea

Making a little distilled water is usually an expensive process in relation to the small amount of distilled water obtained. It seems almost impossible to obtain enough drinking-water from the sea to supply a whole population at an economic price. Nevertheless, it is being done at this moment in places where the natural supply of water is deficient.

I am indebted to the Royal Netherlands Embassy and to Messrs G. and J. Weir, of Glasgow, for information about distilling apparatus installed by Messrs Weir in Curaçao in the West Indies. Difficulties have been overcome by obtaining heat in the most economical way, and by using it to the greatest advantage.

Altogether twenty-two plants are operating in Curaçao. In some of these heat is obtained by using waste heat from diesel engines generating electric power. Others use waste steam from turbo-generators. These are the most economical sources, because the heat would otherwise be wasted. When neither of these sources is available, power and heat are obtained from engines using diesel oil or boiler oil.

The plant is so designed that little heat is lost by radiation. The evaporation is carried out in six stages; this again provides a means of conserving heat by using the steam heat to the best advantage.

When sufficient steam has been drawn off to leave about three times the normal amount of salt, the water is pumped back into the sea; any evaporation beyond this point would use heat wastefully; further water would evaporate only at a higher temperature. In the self-contained units there are practically no moving parts except the pumps. The pumps raise water to be evaporated, and for use in condensing the steam; they also pump the salt water that cannot be economically evaporated, back into the sea.

Each of the plants in Curaçao provides 300 tons of drinking-water per day.

$$\begin{aligned} 300 \text{ tons} &= 300 \times 2,240 \text{ pounds} \\ &= 672,000 \text{ pounds} \end{aligned}$$

That is the weight of about 67,000 gallons of water. So that the daily output of all the plants is:

$$67,000 \times 22 = \text{about } 1\frac{1}{2} \text{ million gallons.}$$

Messrs Weir have also installed three distilling plants at Aden for the Anglo-Iranian Oil Refineries; each of these supplies 130,000 gallons of drinking-water daily, from sea-water. Ten similar plants are being installed at Kuwait.

The sun's heat has been used for evaporating sea-water in hot, arid countries, but the cost of the plant is very great, and the drinking-water obtained is correspondingly expensive.

Natural Distillation

Nearly all the water in the world, all but a tiny fraction, is salt water. It has to be distilled before we can drink it,

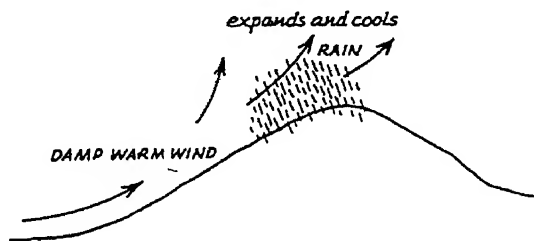


FIG. 7

or before it can be used to water the soil. If we were to water our gardens with sea-water we should turn them into little deserts.

Sea-water is constantly being distilled on a vast scale. Over all the oceans and seas, and from the land also, water is continually evaporating. Pure water turns into vapour and rises into the air. That is the first stage. The water vapour moves with the wind and crosses the land. Then, by one means or another, the vapour is cooled; it condenses, and falls as rain.

In crossing mountains, a damp wind from the sea is forced upward by the mountain slopes. It flows into the cold, low-pressure region above. Here it expands, and in expanding cools. The cooled vapour condenses and falls

as rain. That is why mountain regions usually have a high rainfall, higher at any rate than neighbouring plains.

But there is rain also on the plains, as we all know, and here the vapour is cooled in another way. Part of the plain, warmed by the sun, may be hotter than neighbouring land. Air over the heated region is warmer, and therefore lighter, than surrounding colder air. The heavy colder air presses inward, and forces the light warmer air upward. The warm air expands, and cools. If the cooling is sufficient, the vapour condenses, and falls as rain.

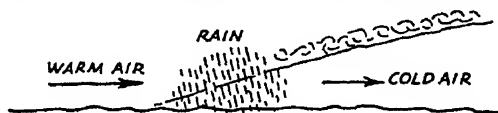


FIG. 8

Sometimes it happens that an advancing 'cold front' of air pushes under warm air in its path; vapour condenses and falls as rain. Or an advancing 'warm front' flows upward across cold air, and, just as when air is forced upward by a mountain range, we once more have rain.

No land can be fertile without water, and for this reason our life on earth is very much dependent on the process of natural distillation.

Brimstone

Brimstone, the 'stone that burns', is the other name for sulphur. We put a little sulphur in a test-tube, and heat it. The sulphur melts to a yellow liquid. We go on heating. The liquid becomes viscous, and then it boils to a bright red gas. The gas condenses at the top of the tube, which is soon covered with a thin layer of solid sulphur. We have actually distilled a small amount of sulphur.

A considerable amount of sulphur is distilled by volcanoes, but a volcano does not produce the pure substance. The sulphur mined in Sicily, for example, is very impure. The old method of dealing with the crude sulphur was to make a kiln in a hill-side. The kiln was filled with lumps of crude sulphur, and fired at the top. Enough of the sulphur burned to melt the rest and the molten sulphur was run off into moulds below.

One of these kilns might burn for two months and yield 200 tons of sulphur. But it was a wasteful method. A third or even half the sulphur might be burned in melting the rest. And the countryside would have the unpleasant sulphur dioxide drifting about, to the detriment of animal and vegetable life. There have been improvements to make the kilns more efficient, but the method is still essentially the same.

The sulphur is still far from pure; it has to be distilled. It is heated in large iron retorts, and the sulphur gas which boils off is admitted to a cool chamber. It sublimes, that is to say it changes directly from gas to solid, and settles on the walls of the chamber as flowers of sulphur. To get the massive form of sulphur, that is brimstone or roll sulphur, the cooling chamber is kept at a higher temperature. The sulphur gas then condenses as a liquid and is run off into moulds.

Sal-ammoniac

Sal-ammoniac is chloride of ammonia. It has a rather odd history. It is mentioned by Pliny, though it is doubtful whether his sal-ammoniac is the same as ours. It was certainly known to the alchemists as long ago as the thirteenth century.

For a long time the only supplies of sal-ammoniac came from Egypt; they were brought to Europe by the Venetians, and afterwards by the Dutch. But it is in the method of getting the sal-ammoniac that the interest lies. Practically the only fuel in Egypt was dried dung. In the first four months of the year the dung contains much sal-ammoniac. The soot from the chimneys was collected in these months, and went to the manufacturers. In March and April the sal-ammoniac factories were busy. The soot was carefully distilled, and the sal-ammoniac sublimed. And so the needs of Europe's chemists were supplied.

Vacuum Pans

There is a fascinating experiment in which we cause water to boil, not by heating, but by cooling.

We fill a flask two-thirds full of water, bring it to the

boil, and let it go on boiling for several minutes to drive out the air. We remove the flame, and then, but not till then, we cork the flask tightly, and rest it upside-down in the ring of a retort stand.

The water soon stops boiling. We squeeze a little cold water over the flask, and the extraordinary thing happens; the water begins to boil again. When boiling ceases another squeeze of cold water starts it anew. This may be repeated quite a number of times.

This is the explanation. Boiling ceases when the vapour pressure, which causes liquid water to change to vapour, is equalled by the pressure of the vapour, above the liquid. Cold water condenses some of the vapour, and so reduces its pressure. The vapour pressure of the liquid is now greater than the pressure above, and so boiling starts again. Thus by reducing the pressure on the water we may have it boiling at a temperature considerably below 100°C .

There are other ways of reducing the pressure on a liquid. We could use a rotating fan to draw away air and any vapour that forms. This is the method used with vacuum pans. It enables distilling to be carried out at a lower temperature than would otherwise be possible. And it enables us to concentrate a solution of sugar, for example, at a lower temperature.

Sugar from Beet

Good sugar-beet contains about 15 per cent of sugar, enclosed in the cells of the plant. The first process consists of extracting the sugar. The beet is washed, and cut into slivers by a machine; we want plenty of surface for diffusion.

The slivers of beet are placed in water in large iron tanks, and the sugar diffuses into the water; it passes from the plant cells to the water. We want to extract as much sugar as possible, so the diffusion is carried out in stages.

(i) Sugar-beet, almost exhausted of sugar, is diffused with pure water. This gives a very weak solution of

sugar. The now exhausted beet is removed, to be used as cattle food, and a fresh lot of beet is brought in.

(ii) The weak solution is used with less exhausted beet, and further diffusion takes place. The process is repeated with still less exhausted beet, and so on, until finally fresh beet is used.

(iii) At each change in the battery of diffusion tanks, one lot of fresh beet is added, and one lot of exhausted beet is removed.

By this means a solution of sugar is obtained which contains almost as great a percentage of sugar as the original beet. Most of the impurities are removed by heating the juice with lime; this precipitates the impurities: they come down as small insoluble particles. The sugar solution is filtered off, and goes to the vacuum pans.

The concentration of the sugar solution is also carried out in stages. The first pan is heated by steam, and steam from this pan is used to heat the second pan, which is kept at a lower pressure. Steam from the second pan is used to heat a third, which is kept at a still lower pressure. Thus the final concentration is done at a comparatively low temperature, and there is little fear of the sugar being burnt.

The concentrated solution is allowed to cool, and the sugar crystallizes. The syrup may be drained away by placing the sugar in a centrifugal machine. The syrup is swished out through the meshes of a net which retains the sugar.

Distilling Alcohol

Alcohol is an important liquid. It is used in various degrees of concentration, from 3 to 7 per cent in beer, up to 100 per cent in absolute alcohol. It is used industrially in the manufacture of paints, varnishes, polishes, and perfumes, as a fuel in spirit lamps, and in the manufacture of many fine chemicals and medicines.

Alcohol is usually produced by fermenting sugar or starch. Yeast is necessary to the process, and during fermentation the liquid is kept at a warmish temperature.

The percentage of alcohol in the fermented liquid is always low, so the process of concentration is important. We start with a little alcohol in a lot of water, and we want to increase the proportion of alcohol.

Every liquid which is not changed chemically by heating has its own particular boiling point. Alcohol boils at 78°C ., and water at 100°C . It might seem that if we kept the temperature at about 80°C ., the alcohol would be distilled, and the water be left behind.

But it is not quite as easy as that. The molecules of alcohol are evidently more mobile than those of water; it is easier to jerk them into the gaseous state. But water also evaporates. Below 100°C . the evaporation of alcohol is more rapid than that of water, but distillation does not give us 100 per cent alcohol.

If we were to go on distilling till all the original liquid had boiled away, we should have a condensed liquid very much like that with which we started, so far as the proportions of alcohol and water are concerned. What we do is to take the first portion of liquid that distils, for this is certainly much richer in alcohol.

A second distillation of the enriched portion would give a liquid still richer in alcohol. This method of separating liquids is called fractional distillation. But there is a limit to what can be achieved by repeated distillations.

It is possible to get a mixture of 96 per cent alcohol and 4 per cent water. But that mixture is a *constant boiling mixture*; water and alcohol distil as if they were a single liquid, so there is no further separation.

Absolute Alcohol

To get 100 per cent alcohol we have to use other methods. We want something that will absorb the water and leave the alcohol. One method is to use lumps of quicklime about the size of walnuts. These are left in the liquid for several days, and the liquid is then distilled. A second treatment with quicklime yields just about 100 per cent alcohol.

The strength of an alcoholic liquid is usually described

as so many degrees over proof or under proof. Proof spirit contains very nearly one part by weight of alcohol to one part of water. To find the percentage of alcohol we add, or subtract, half the number of degrees to, or from, the 50 per cent of proof spirit.

Distilling Spirits

The famous illicit stills of the Highlands of Scotland and Ireland were primitive appliances for the fractional distillation of alcohol and water. Often there was a

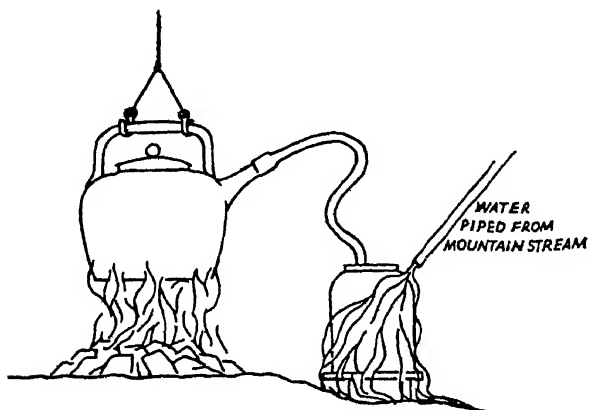


FIG. 9

large kettle to boil fermented liquid containing alcohol. Some sort of a jar was used as a condenser, with cold water from a mountain stream pouring over it, and a tube connecting boiler and condenser.

The stills were used to produce whisky by distilling fermented barley. Excise officers were very thorough in their search for illicit stills, because taxation on spirits was always very high.

The various kinds of spirits are made by distilling different fermented liquids to increase the percentage of alcohol from perhaps 3 or 4 per cent to as much as 50 per cent, or even more. Volatile essences are given off with the alcohol

in distillation, and these give the flavours which distinguish various kinds of spirit. Brandy is made by distilling wine; it is alcohol and water, with flavour that comes originally from the grapes. Rum is distilled from fermented molasses; the flavour comes from sugar-cane. Scotch whisky and Irish whiskey are usually distilled from fermented barley, but rye and other grains are used. Gin is a colourless spirit made by distilling any fermented liquid with juniper berries.

Methylated Spirit

Methylated spirit is not meant to be drunk. It is purposely made unpleasant, so that there may be little temptation to drink it.

Ordinary alcohol obtained by fermentation of sugar or starch, is ethyl alcohol. Methyl alcohol is another alcohol obtained under high temperature and pressure, from carbon monoxide and hydrogen. It is definitely poisonous, and it is added to ethyl alcohol to make it undrinkable.

The methylated spirit used for industrial purposes contains about 4 per cent of methyl alcohol and 85 per cent of ethyl alcohol; the rest is water. The methylated spirit usually sold is made even more unfit to drink. In addition to the two alcohols it contains colouring matter and a small percentage of unpleasant-tasting petroleum.

Unpleasant liquids are added to industrial alcohol to make it unfit to drink. In this way it may be sold free of the very high duty which has to be paid on spirit that is used for drinking.

Distilling Air

It is possible to distil air because we can produce liquid air by compressing it and reducing it to a very low temperature. The possibility of fractional distillation depends also on the boiling points of the component gases being fairly wide apart. Air, freed from water and carbon dioxide, contains the gases in the following table. The boiling points are given in degrees absolute (K.), that is,

with absolute zero as the zero of the scale, as well as in degrees Centigrade.

	<i>Boiling point</i>	<i>Difference between the boiling points</i>
helium . . .	4° K. — 269° C.	23°
neon . . .	27° K. — 246° C.	50°
nitrogen . . .	77° K. — 196° C.	10°
argon . . .	87° K. — 186° C.	3°
oxygen . . .	90° K. — 183° C.	30°
krypton . . .	120° K. — 153° C.	45°
xenon . . .	165° K. — 108° C.	

The differences are considerable, except for argon and oxygen. The bulk of the gas consists of oxygen, roughly a fifth, and nitrogen, about four-fifths; argon forms about 1 per cent. The first stage is to get oxygen pure enough for most purposes; we want it freed from the great bulk of nitrogen. The distillation has to be conducted at a very low temperature and in very special apparatus. The small percentage of argon (inert) which accompanies the oxygen is unimportant for industrial processes.

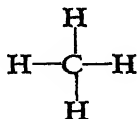
At a rather higher temperature the oxygen and argon can be boiled out, leaving a small quantity of krypton and xenon. These can be separated at a still higher temperature.

Neon can be obtained by distilling liquid air at a very low temperature. The neon distils in a pure state because of the wide difference of 50° between its boiling point and that of nitrogen. Helium also could be obtained in this way. But the air is a poor source of helium; there are only 56 parts by weight of helium in a hundred million parts of air. A better source is the natural gas from oil wells.

Distilling Oil

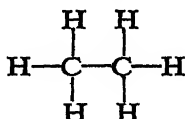
Crude mineral oil, as it comes from the oil wells, is a mixture of a large number of substances. Most of these are hydrocarbons, which are compounds of hydrogen and carbon. And the greatest number of them belong to the group called paraffins. There are also aromatics and naphthenes. All these compounds have carbon atoms linked together in a kind of skeleton to which other atoms attach themselves.

In the paraffins, the carbon atoms are linked in chains. The simplest of all consists of one carbon atom linked to four hydrogen atoms.



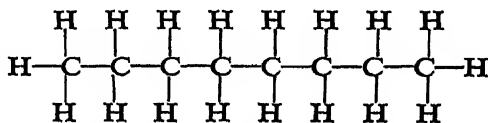
This is the molecule of methane, or marsh gas, which forms more than a third of coal-gas.

The next in simplicity is two linked atoms of carbon, with six atoms of hydrogen linked to the free valencies.



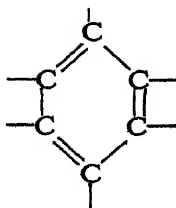
This is the molecule of ethane, another gas which is present in coal-gas.

We may have a carbon skeleton consisting of 3, 4, 5, 6, or 7 linked carbon atoms. The next paraffin has 8 linked carbon atoms, with 18 hydrogen atoms.

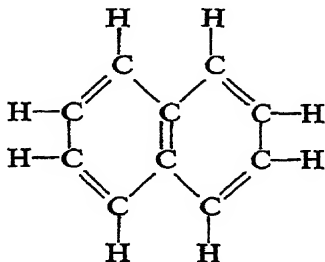


This is the molecule of octane. Higher paraffins have still more linked carbon atoms.

The aromatics have the carbon skeleton arranged as a ring, the benzene ring, which is usually represented as :



In benzene itself there is a single hydrogen atom to each of the six free valencies. Naphthalene has a double ring of carbon atoms with a hydrogen atom to each free valency:



The paraffins, aromatics, and naphthenes exist separately in the crude oil, and also combined with one another.

The smallest molecules are the easiest to stir into gaseous activity, and so liquids with small molecules have the lowest boiling points. Hydrocarbons with molecules containing one, two, or three carbon atoms, have boiling points far below zero. Then as the molecules become more complex, the boiling point rises progressively. So it should be possible to get at least partial separation by fractional distillation.

Bubble-caps

Oil refining is carried out in a fractionating tower. This has a number of chambers one above another. They are connected in an interesting way, by means of *bubble-caps*. Small tubes pass through the ceiling of a lower chamber and rise to a height of a few inches above the floor of the chamber above. Over the end of each tube is a saucer-shaped cap. The floor of the higher chamber is flooded with condensed oil. Gas forced up from below is compelled by the cap to bubble through the liquid which floods the floor. Any gas of higher boiling

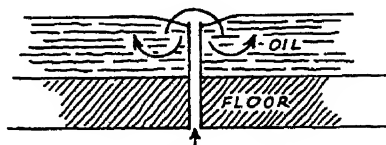


FIG. 10

point is cooled sufficiently to be left behind in the liquid oil. Any gas of lower boiling point is insufficiently cooled to condense; it is forced upward, to condense in one or more of the higher chambers.

Fractionating

The crude oil is heated in closed retorts, so that air cannot get to it. At a temperature of 520°C . the gas which boils off is admitted at the base of the fractionating tower. In the lowest chamber the liquids, with the highest boiling point condense. This is the *heavy distillate* fraction, with long paraffin chains of carbon atoms, or other heavy molecules.

The remaining gas rises into the next chamber, which may be kept at 300°C . Here the liquid used as diesel fuel condenses.

In the next chamber the temperature may be 200°C ., and here naphtha condenses. Then at 100°C . gasoline, or petrol, condenses. In the highest and coolest chamber we get light oil, with only three or four atoms in the carbon skeletons.

Thus the crude oil has been distilled into six fractions:

- (i) Light oil.
- (ii) Gasoline, or petrol, with a fair proportion of octane.
- (iii) Naphtha, or paraffin oil.
- (iv) Diesel oil.
- (v) Heavy oil.
- (vi) The residue, asphalt.

The temperatures may be varied, to increase, or decrease, one or more of the fractions. And the number of fractions may be increased by having more condensing chambers, and a slighter change of temperature from chamber to chamber.

Cracking

The most desirable of the fractions is petrol, so we want to increase the yield of this valuable oil. This can be done by the process known as *cracking*. We may

have a paraffin molecule with sixteen carbon atoms, and therefore thirty-four hydrogen atoms (one above and one below for each carbon atom, plus the two at the ends). If we could break it in two we might have two chains of eight carbon atoms, but there would be insufficient hydrogen. One carbon atom may be ejected and we might have molecules of heptane (seven carbon atoms) and octane (eight carbon atoms).

Heavy gas is subjected to high pressure and high temperature. The long molecules are thrown into violent agitations, and the chains crack. Thus the yield of lighter oil is increased.

Cracking is now brought about by passing the heavy oil over beds of finely powdered molybdenum or platinum. When platinum is used, the process is known as *platforming*. One of the difficulties of the process is that carbon is deposited on the platinum, and chokes it. This has been overcome by having the platinum on a moving bed, so that it flows out into a chamber where the carbon is burnt off, and it is then ready to be used again.

Distilling Coal

The old method of distilling coal, destructively, was similar to the process of charcoal burning. The object in both cases was to produce a solid fuel suitable for iron smelting.

When coal was being distilled, a pile of coal was built up round a brick chimney. The pile might be 30 feet across and 5 or 6 feet high. It was covered with wet coke dust to check wasteful burning. The fire was started by dropping live coals down the chimney. The heap was allowed to burn for five or six days; and during all that time the ventilation had to be carefully watched. If the fire burned through to the outside, the hole was plastered over with more wet coke dust.

Volatile materials came off from the hot mass as smoke. When no more smoke poured out, the ventilation was completely smothered with damp coke; and the hot mass was allowed several days to cool.

Coke used for smelting is still made by subjecting coal

to long, slow heating; the process is now carried out in retorts, or ovens. Coke made in this way is harder than the coke from gas-works. It does not burn easily, so it is not suitable for open fires. But it is an excellent fuel for blast furnaces. It burns furiously in the intense blast; and it can endure the pressure of a hundred feet of material above it in the furnace without being crushed.

What the Gas-works Do

In gas-making, coal is distilled for a much shorter time, at a higher temperature. The temperature is about 1000°C ., rather higher than cherry-red heat. The coal is heated in large iron retorts, and air is excluded to keep the gas from burning, and so being wasted.

We can imitate the method with a syrup tin for the retort. We fill the tin with small coal, make a nail-hole in the lid, and press the lid down firmly. We heat the tin over a gas-ring. After a time smoke pours out through the hole; when it is coming off strongly we put a lighted match to it. We should get a bright flame from the burning gas.

In gas-works the smoky gas from the gas-ovens is passed into water, which condenses the smoke. The colourless gas which emerges is the familiar coal-gas. It is a mixture of many gases: methane, ethylene, and other hydrocarbons, as well as carbon monoxide and free hydrogen. Each of these gases contains at least one of the two combustible elements, carbon and hydrogen.

The smoke settles, under water, into the black, sticky stuff called coal-tar. The water also contains valuable substances in solution. There is nitrogen in coal, and this comes off as the very soluble ammonia, or one of the soluble salts of ammonia, especially the sulphide and carbonate.

Thus the first stage of destructive distillation of coal gives us:

- (i) Coal-gas, a mixture of combustible gases used for lighting and heating.
- (ii) Ammonia and salts of ammonia. These are

used in fertilizers, and have many lesser uses in the chemical industries.

(iii) Coal-tar.

(iv) The final residue of coke in the gas-oven. This is used as a fuel in open fires.

Coal-tar

The black, sticky coal-tar was formerly regarded almost as a waste product. Some of it was even used in paving roads. Now it is known to be a very valuable product indeed. The transformation of this all-but-waste material into a long range of useful products is one of the glories of chemistry.

To begin with, the coal-tar is fractionated by distilling. It is usually divided into four fractions:

(i) With a temperature of up to 210°C . we get light oil.

(ii) With the temperature raised to 240°C . we get carbolic oil.

(iii) With the temperature raised to 270°C . we get creosote oil.

(iv) Over 270°C . we get anthracene oil.

And there is a final residue of pitch which is a mixture of the higher hydrocarbons with long carbon skeletons. Pitch can be used as a fuel or for surfacing roads.

On the four important fractions chemical magic gets to work.

Transformation of Light Oil

The light oil is shaken up with sulphuric acid, and afterwards with caustic soda. It is then distilled once more, into benzene, toluene, and xylene.

Benzene is a colourless liquid which is lighter than water. It burns with a bright, smoky flame. It is an excellent solvent for organic substances; it can be used, for example, to remove grease spots from cloth materials. It has to be used with care because it is highly inflammable.

When benzene is being used commercially as a source of dyes, it is chlorinated to give chlorobenzene. This is treated with ammonia, to produce aniline. And the aniline may be oxidized to give nitrobenzene, that is, it is caused to unite with oxygen.

Aniline is an oily, poisonous, colourless liquid, which turns brownish when it is exposed to the air. It is the basis of the aniline dyes. The first of these dyes was mauve, and was made by Sir William Perkin in 1856. He oxidized aniline with potassium dichromate.

Aniline black is another dye which is formed by the oxidization of aniline. It is one of the dyes which are formed in the actual fibres of the material being dyed. The material is placed in a solution of aniline hydrochloride, and a chlorate is added to supply oxygen. A trace of a vanadium salt is necessary to provide a catalyst. If the oxidization is complete the dye is permanent. If it is incomplete the material takes on an unpleasing greenish look.

There are hundreds of aniline dyes, some of them extremely vivid.

Toluene is a colourless liquid, and like benzene it is a good solvent for organic compounds. It is used in the manufacture of saccharin, and also in the production of dyes. But its chief title to fame is that it is used in making the explosive T.N.T., which stands for trinitrotoluene. As the name suggests, it is made by treating toluene with nitric acid. A mixture of nitric acid and sulphuric acid is made, with some additional sulphur trioxide. Toluene is run into the mixture. T.N.T. forms pale-yellow crystals which darken to reddish-brown. It is a convenient form of explosive because it is not set off by friction or percussion; it has to be detonated. It is chiefly used for filling shells. It is also mixed with four times its weight of ammonium nitrate to form amatol, an explosive which is used in blasting.

The xylene distilled from light oil is a mixture of three very similar liquids. Like benzene and toluene, it is a good solvent for organic compounds. It is used in making vivid scarlet dyes.

Carbolic oil

The carbolic oil consists chiefly of phenol, which is carbolic acid, and naphthalene.

Phenol, which forms needle-shaped crystals, is a versatile compound. It is a good disinfectant and antiseptic. It has, however, the disadvantage of being poisonous; it is not suitable as a dressing for wounds. Phenol is used in making aspirin and in dye-making.

There is another odd use of phenol. When it is heated with formaldehyde it forms a plastic resin that can easily be moulded. This resin is soluble in alcohol, and fusible. But when it has been baked it ceases to be either soluble or fusible. It becomes the hard substance called bakelite, which is used for numerous small articles, especially those used as electrical insulators.

Naphthalene forms white, flat crystals. It is chiefly used in dye-making. And quite a large amount of it goes into moth-balls.

Creosote and Anthracene Oils

Creosote oil consists chiefly of three very similar liquids, the cresols. The cresols may be treated with nitric acid to give the yellow dye called Victoria yellow. But their chief importance is that they are powerful disinfectants.

Anthracene is used in making alizarin, one of the most important dyestuffs. Alizarin forms red crystals. It reacts with metallic salts to form insoluble pigments of the kind that are called *lakes*.

If anyone should think there is not a sort of quasi-magic about chemistry, let him think again about what chemistry has conjured out of the black waste of coal-tar. Brilliant dyes; high explosives; antiseptics; solvents for paints and varnishes; cleansing liquids; aspirins; saccharin; bakelite; and still more and more dyes.

III

SOLUTIONS

1. In what ways do solutions affect our lives?
2. Which substances are extremely soluble in water?
3. How may sand and salt be separated?
4. How can muddy water be cleared without filtering?
5. What is a sol?
6. Why is alum put into swimming-baths?
7. How do chemists separate salts of two metals?
8. Which salts are found in sea-water?
9. What peculiarities are there in the salinity of the Baltic?
10. Why is the Mediterranean more salt than the Atlantic?
11. Why are completely landlocked lakes usually salt?
12. Why is the Caspian not very salt?
13. How is salt obtained from the sea?
14. What is *sel gris*?
15. Where are great salt deposits found?
16. What is there odd about the solubility of ammonia?
17. Which is the most important solution of a gas in water?
18. How are large crystals obtained from solutions?
19. How is crystallization speeded-up?
20. Which are the two important classes of solvent? How do they differ?

CHEMISTS depend greatly on solutions, and there are very good reasons why they should do so. In a solution solid matter is reduced to a very fine state, so fine that it passes through a filter-paper which restrains even the minute particles of a suspension. Thus, when two solutions are mixed, the substances dissolved are brought into very intimate contact, and so are able to react readily. And solutions are easy to stir so that we can bring about even more complete contact.

Chemists are not alone in their dependence on solutions. Cooks depend for the palatability of their concoctions on the concentration of their solutions of salt and sugar and the more delicate flavours. Too little salt in the solution, and the food is insipid; too much salt, and it is nauseating. Doctors, who are apt to appeal to chemists to help them out, often dose us with solutions. They do indeed sometimes prescribe suspensions, and then we are urged to shake the bottle. Gardeners use weak solutions to encourage their plants to greater and more rapid growth. Without such weak solutions, either natural or artificial, there would be no plants, and therefore no animals. We are all of us continually dependent on solutions for our very existence.

Degrees of Solubility

Water is the great solvent. It is so commonly used as a solvent that when we say a substance is soluble we usually mean that it dissolves in water. If we use alcohol or some other liquid as the solvent we take care to specify what the solvent is.

Some substances dissolve in water much more readily than others. We put sugar in our tea, if we like it sweet, and stir the tea. The sugar readily dissolves, and sweetens the tea. We get no taste until the sugar is dissolved, and can thus be brought into intimate contact with the organs of taste. If we have a very sweet tooth, we can stir in, and dissolve, several spoonfuls of sugar. But the practice is not to be commended. When we are making jam we put three-quarters of a pound of sugar, or even more,

to a pound of fruit, and we find that it dissolves readily enough in the hot mush. Sugar is indeed extraordinarily soluble in water. Half a pint of water, at room temperature, would dissolve more than a pound of sugar; and if the water were raised to boiling point it would dissolve about three pounds of sugar. A pound to a pound is, however, just about the upper limit for jam. If, pandering to a very sweet tooth, we were to add much more sugar, the sugar would not remain in solution when the jam cooled; the jam would have a 'sugary' texture.

Common salt, washing-soda, saltpetre, potassium chlorate, and a great variety of other substances, dissolve readily in water. Silver nitrate is extremely soluble. Water at room temperature can dissolve about twice its own weight of silver nitrate, and when the temperature is raised to boiling point, nine and a half times its own weight.

Lime is an example of a substance that dissolves sparingly in water. Water, which dissolves twice its own weight of silver nitrate, dissolves only a six-hundredth of its weight of lime. Sulphur and chalk are examples of substances so sparingly soluble that they are generally considered quite insoluble.

Separating Salt and Sand

We have an easy way of separating two substances when one of them is soluble and the other insoluble. We shake up the mixture of solids with water, and that alone makes a sort of separation. The soluble substance is dissolved in the water, and the insoluble substance begins to settle to the bottom. We can get a better separation, if we decant, or pour off, the clear liquid containing the soluble substance.

For complete separation we can use a filter. Up-to-date laboratories are more and more tending to use *centrifuges* instead of filters. These get rid of the unwanted solution by whirling it away.

However, there are points of interest about the use of filter-papers. The liquid containing the dissolved solid passes through the filter-paper, and can be collected in a

jar. The insoluble substance is left behind on the filter-paper.

There is still a little of the soluble substance left in the damp deposit on the filter-paper. We can get rid of it by blowing a thin stream of water on it, and we can then dry the insoluble substance which remains. The soluble substance is recovered by carefully boiling away the water from the solution.

A mixture of salt and sand can be separated without even using a filter. We put the mixture in a jar, and stir it up with a little water. We let it settle for a moment, and then pour off the clear liquid. This contains most of the salt; we can recover it in solid form by boiling away the water. To free the sand of salt we fill up the jar with water, stir it, let it settle, and pour off the clear liquid. When this has been done several times, the sand will contain no detectable trace of salt.

We can use crushed chalk instead of sand for the experiment just described. When sand is used it should first be washed free from clay. To do this we put the sand in a jar, fill it with water, and stir it up. If the water is at all murky we pour it out. We repeat this several times till the water is quite clear after stirring. Incidentally, before sand is put into an aquarium it should be thoroughly washed in this manner.

Clearing Murky Water

When we are washing sand we can hardly help noticing that the clay which washes out forms a very fine suspension. Unless we pour it away it hangs about in the water and settles only with great slowness, if at all. We can get the suspension to settle to the bottom of the water by stirring in a little salt.

Here is an experimental test. We fill two jars with water, put a little clay in each jar, and stir well, so that the clay is finely dispersed in the water. We add a teaspoonful of salt to one jar only, and stir again to dissolve the salt. We leave the jars undisturbed for a day or two. We find that water in the jar to which salt is added clears much more quickly than the other. Salt causes

the suspended particles of clay to coagulate, or come together in small lumps. Very fine silt attaches itself to the coagulated lumps, and sinks with them. As a result the water becomes really clear.

Colloidal Solutions

In an ordinary solution the particles of dissolved solid are of extremely small size, the size of molecules. In a suspension the particles are much bigger, and may be big enough to settle as precipitates. Between the two we may have particles of intermediate size, and these form what are called *colloidal solutions*, or more shortly *sols*.

There is a simple way of distinguishing between the three states. A filter-paper stops the suspension because the mesh is too small for the particles to go through. But the mesh is big enough to allow both colloidal particles and dissolved matter to pass through. In parchment paper the pores are smaller. Parchment paper stops the colloid, but allows the dissolved matter to go through.

In all sols the particles carry electric charges. In some sols the charges are positive, and in other sols they are negative. It is the charges, like charges in any sol, that keep the particles apart. This has been shown by applying an electric field to a sol. The particles are attracted to the pole of opposite charge. There they give up their charges. And so they no longer repel one another; they coagulate and fall as a suspension.

If we can neutralize the colloidal particles in any other way we should expect coagulation. Clay forms a negative sol. Common salt introduces the positive sodium ion, that is the sodium atom with a positive charge. This has the desired effect, and the particles of clay coagulate.

Aluminium is far more effective than sodium for precipitating a sol. The sodium ion has one positive charge only, whereas the aluminium ion has three. For this reason a very little alum is often used, in swimming-baths for example, to precipitate objectionable colloidal matter.

Some of the devices for clearing water of mud probably

arose out of practical experience, unassisted by the theory which, had it been known, might easily have suggested better methods. A great many people are dependent on the muddy River Nile for their drinking-water. It is said that they clear the water by rubbing the insides of drinking-vessels with bitter almonds. Oak chips are sometimes used for the same purpose. Their effectiveness is ascribed to the tannin which they contain.

It is a common enough practice to pour spent tea-leaves and used coffee grounds down the drain pipes to clear kitchen sinks. It is a practice not without good chemical warrant. Both tea and coffee contain tannin; hence the bitterness of stewed tea. The tannin coagulates waste in the pipes, and so helps to clear them.

Moses cleared the bitter water of Marah, in the wilderness of Shur, by casting a tree into it. It has been suggested that Moses used a tree that would coagulate colloidal matter in the water, and so clear it. He might very well bring knowledge of such a tree from Egypt.

Separating Substances

The method used in separating sand and salt is a standard one used by chemists in separating substances. We aim at producing a salt of one substance which is soluble, along with a similar salt of another substance, which is insoluble. The chief difficulty is to produce such a pair of opposites. As soon as we have got them, the separation is usually not very difficult.

If the material we are dealing with is not soluble, we begin by making it soluble. We test it with hydrochloric acid and other reagents until we find one that produces soluble salts of both substances in the mixture.

The next step is to precipitate one of the substances, say one of two metals. We go on testing till we find a suitable reagent, that is, one which precipitates one metal only.

It is much easier if we know the metals we are dealing with. We know the properties of the various salts of the metals, or we can look them up. With this knowledge, we can choose suitable reagents for the two

processes: solution of both metals, and precipitation of one only.

When the metals are unknown we have to go by probabilities. We may get complete solution with nitric or hydrochloric acid, and we then have to test till we find a reagent which produces an insoluble salt of one metal.

The Oceanic Solution

The greatest of all solutions is the mighty ocean which covers about three-quarters of the globe to an average depth of 2 miles. Rivers run down to the sea and carry with them anything that is soluble in their basins. The soluble material accumulates in the sea. The sea does indeed lose some salt when high winds blow. The surface is tossed into spray, and the salt spray may be blown far inland. But such loss is comparatively small, compared, that is, with the vast amount of salt in the sea. Most of the water that leaves the sea is pure water that evaporates.

By far the greater part of the matter dissolved in the sea is common salt, sodium chloride. But there are many other salts. The commonest are:

magnesium chloride and sulphide
calcium sulphate and carbonate
potassium sulphate
magnesium bromide

And there are lesser quantities of salts of:

silicon	iron	manganese
fluorine	lead	copper
silver	gold	arsenic
iodine	uranium	

and other elements. The presence of gold and silver in sea-water arouses one's cupidity. There is indeed a lot of these metals.

I have seen the amount of silver in the oceans estimated at 10,000 million tons but no calculation was given to justify the estimate. The best I can do is the following:

The mass of the ocean is given, with a rather suspicious appearance of accuracy, as:

$$1.45 \times 10^{24} \text{ grams}$$

(A kilogram is 1,000 grams. A metric ton is 1,000 kilograms, or a million grams.)

$$= 1.45 \times 10^{18} \text{ tons}$$

Rankana and Sakhamra give the amount of silver as:

$$0.0003 \text{ gram per ton}$$

So the total amount of silver is:

$$\begin{aligned} & 1.45 \times 0.0003 \times 10^{18} \text{ grams} \\ &= 1.45 \times 0.0003 \times 10^{12} \text{ tons} \\ &= 4.35 \times 10^8 \text{ tons} \\ &= 435 \text{ million tons.} \end{aligned}$$

In a calculation of this kind the $1\frac{1}{2}$ per cent by which the metric ton undercuts the British ton is not very important. We can consider the result as about 430 million tons of either kind.

The amount of gold is given as 0.00004 gram per ton. We take a tenth of 435 million and increase it by a third (that is, multiply by $\frac{4}{3}$):

$$43.5 \times 10^6 \times \frac{4}{3} = 58 \times 10^6$$

So there are 58 million tons of gold.

These are vast amounts of the precious metals. Unfortunately, they are dispersed through an intolerable deal of water: 3 grams of silver in 10,000 tons of sea-water; 4 grams of gold in 100,000 tons of sea-water. There seems to be more than ten times as much arsenic as silver. But again, no one requiring arsenic would go to the sea for his supply.

The cost of collecting these substances from sea-water would be vast compared with the very small result. We have, however, an unpaid assistant in collecting iodine. Seaweeds collect iodine, and the ashes of burnt seaweeds were formerly the chief source of that element.

And nowadays modern techniques for collecting elements which occur only as traces are so effective, that sea-water may well be used in the future as a source of some of the rarer elements.

Salt in the Atlantic

The ocean is quite a strong solution as anyone who has ever swallowed a mouthful of it knows. In mid-Atlantic a gallon of water contains about 5.4, or nearly $5\frac{1}{2}$, ounces of dissolved salts.

The proportion of salt varies from place to place, as one might expect. In Polar regions a lot of fresh water reaches the ocean in the form of melting icebergs, so the salinity is comparatively low; it is about 4.7 ounces to the gallon, nearly $4\frac{3}{4}$ ounces. In Equatorial regions, where the temperature is high, there is a great deal of evaporation, and much pure water is thus removed from the sea. The salinity is therefore rather greater; it is 5.75, or $5\frac{3}{4}$, ounces to the gallon.

Salinity of the Baltic

The salinity of the Baltic Sea is extraordinary. The surface waters have less than an ounce of salt to the gallon, less than a quarter of the salinity of mid-Atlantic. There are two good reasons for this extremely low salinity. The first is that many great rivers flow into the sea, and bring in large quantities of fresh water. The second reason is that owing to the cool climate there is comparatively little evaporation. More fresh water is gained from the rivers than is lost by evaporation.

Consequently there is an outward surface current through the Skagerrak. This current carries with it salt, which is thus lost to the Baltic. If that were all, the Baltic would eventually become a vast fresh-water lake. But it is not all. Below the surface of the Skagerrak there is an inflow of water from the much more salt North Sea. There appears to be a balance between the amount of salt carried out by the current, and the amount flowing in below. The salinity of the Baltic is more or less fixed.

There is another interesting point about the salinity of the Baltic. The bed of the sea is uneven; here and there are parts of much greater depth than the average. It has been found that salinity is very much greater in these depths. This is good evidence that the Baltic was once a really salt sea, and that it is chiefly the surface salt that is being carried away.

The Salt Mediterranean

In the Mediterranean Sea there is a reverse state of affairs. Comparatively few great rivers flow into the sea; along the southern shore the Nile is the only great river; so there is not a great influx of fresh water. The climate is warm or hot, so there is much evaporation. For both these reasons the salinity is high; it is 6 ounces to the gallon, compared with about $5\frac{1}{2}$ ounces in mid-Atlantic.

There is an inward surface current through the Strait of Gibraltar, and this adds oceanic salt to the Mediterranean: for the salt remains, though some of the bulk of the ocean water is lost by evaporation. There is also an outward current below the surface of the Strait. This compensates, to some extent at least, for the inflow of salt above, especially as it carries off the more salt Mediterranean water.

Salt in the Caribbean and China Seas

The Caribbean Sea is another enclosed sea, though not nearly so completely enclosed as the Mediterranean. The climate is even hotter than the warm Mediterranean climate. As a result, the Caribbean is more salt than the outside ocean but less salt than the Mediterranean.

The China Sea exhibits a peculiarity which is found, less noticeably, in other enclosed seas. In November, at the end of the wet south-west monsoon, the amount of salt is found to be 4.44 ounces to the gallon. After two months of the dry north-east monsoon, and rapid evaporation, the salinity is found to have risen to 5.48 ounces per gallon.

Lakes without Outlet

Lakes, and lakes big enough to be called seas, are usually salt when they have no outlets to the open sea. This is the explanation: rivers flowing into them carry a little salt in solution. The only water that leaves them is the pure water lost by evaporation. There is therefore a slow accumulation of salt in the sea or lake, until eventually we have a salt lake or a salt inland sea.

When there is an outlet, the out-flowing river carries away salt, there is no accumulation, and the lake is a fresh-water lake. Lake Titicaca, on the Andean plateau, is, however, unusual. It is a fresh-water lake in spite of the fact that it is completely shut off from the ocean. This is because a river flows out of it, and deposits the salt in a salt marsh.

The Dead Sea is an extreme case of the accumulation of salt. At the south-west corner of the sea is the Ridge of Sodom, a range of salt hills 7 miles long and about 300 feet high. Salt washes down from these hills and is added to the extreme saltiness of the sea. The amount of dissolved salt is about nine times what there is in the open ocean.

Sea salt has practically the same composition in all parts of the ocean, at any rate so far as concerns the principal ingredients. But the composition of Dead Sea salt is radically different. Oceanic salt contains about four-fifths of sodium chloride, Dead Sea salt contains only about three-tenths. On the other hand, magnesium chloride, which is only a minor ingredient of oceanic salt, makes up considerably more than half of Dead Sea salt.

American Salt Lakes

In the western part of the United States there are many salt lakes, shut off from the ocean, and in arid regions. The biggest of these lakes is Great Salt Lake, in Utah. It appears to be the chief remaining part of a much greater salt lake, which dried up until only the deepest basins were left, filled with very salt water.

The salinity of Great Salt Lake is five or six times as

great as that of the open ocean. The composition of the salt is not unlike that of the ocean, except that there is a bigger proportion of sodium chloride, and a lesser proportion of magnesium chloride. The extreme salinity of the lake appears to be due to the fact that previously deposited salt has been washed into it by rivers.

Lake Searle, in California, is a salt lake that is now almost dry, though it still contains water, especially in the muddy bottoms. A gallon of the lake brine contains nearly $3\frac{1}{2}$ pounds of salts, compared with $5\frac{1}{2}$ ounces in the Atlantic. The deposits in this lake are of some economic importance. They supply about half the world production of lithium, and also of borax, as well as many other minerals.

The Exciting Caspian

The Caspian Sea is extraordinary and exciting. It is completely surrounded by land, it has no outlet to the ocean, and there are indications that it was formerly joined to the Black Sea. So there seems every reason to expect it to be a salt sea, and even a very salt sea.

It is anything but that. At the northern end of the sea, where the great rivers flow in—the Volga, the Ural, and the Terek—the water is often fresh enough to be drinkable. Even the southern half of the sea has less than half the salinity of the ocean.

The explanation of this unexpectedly low salinity seems to be as extraordinary as the fact itself. Round the great sea there are numerous natural evaporating pans. The biggest of these is the large bay called Kara Bogaz half-way along the eastern side of the sea. This great bay is

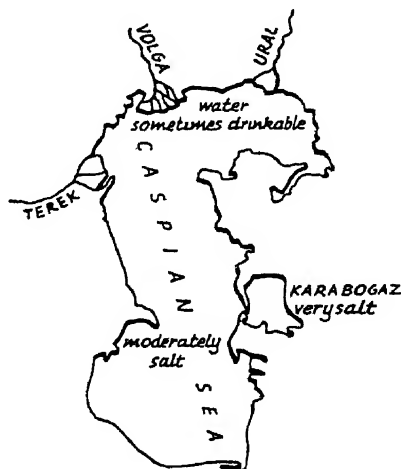


FIG. 11

90 miles across, and it is almost completely shut off from the Caspian. The opening into it is only 150 yards wide, and a mere 5 feet deep.

Evaporation is excessive in the bay, especially in summer. This is due partly to the great heat, and partly to the fact that the bay is open to drying winds from the arid lands to the east of the Caspian. There is therefore a strong current into the bay from the sea outside. This current has a speed of $3\frac{1}{2}$ miles per hour. And because of the shallowness of the entrance, there is no outward current. The situation is rather similar to that of Lake Titicaca.

The amount of water flowing into the bay in twenty-four hours is:

$$\begin{aligned} & 3\frac{1}{2} \times 24 \text{ miles} \times 150 \text{ yards} \times 5 \text{ feet} \\ &= 3\frac{1}{2} \times 24 \times 5280 \times 450 \times 5 \text{ cubic feet} \\ &= \text{very nearly 1,000 million cubic feet.} \end{aligned}$$

The amount of salt in the water is rather less than 2 ounces to the gallon, or say about 12 ounces to the cubic foot. So the total amount of salt carried into the bay in twenty-four hours is:

$$\begin{aligned} & 1000 \times 10^6 \times 12 \text{ ounces} \\ &= \frac{1000 \times 10^6 \times 12}{16 \times 2,240} \text{ tons} \\ &= \text{over 300,000 tons per twenty-four hours.} \end{aligned}$$

That is probably an over-estimate as a daily average for the whole year. But, on the other hand, there are numerous lesser evaporating pans along the coasts, and these must add considerably to the weight of salt withdrawn from the Caspian Sea. It seems probable that the yearly amount of salt withdrawn must be at least 120 million tons. And that, proceeding year by year, and century by century, would account for the comparative freshness of the water of the Caspian Sea.

Salt from the Sea

Men want salt. They need it to give flavour to otherwise insipid food. They want it so badly that on occasion they have fought wars for the possession of salt springs.

Plato called salt 'a substance beloved of the gods'. Christ said to his disciples, 'Ye are the salt of the earth'. Cordelia, according to one version of the story, expressed her affection for King Lear by saying she loved him as much as salt. The story turns into a tragedy because Lear failed to appreciate the simile. Supposing he had been a chemist, or a cook!

Countries which border on the sea can draw upon the boundless oceanic store of salt. Four-fifths of sea-salt is sodium chloride, and that is the salt we want for pot and table. The method of obtaining salt by allowing sea-water to evaporate is specially suited to hot, dry climates where evaporation is rapid. For this reason it has long been practised in Mediterranean countries.

When salt is to be obtained from the sea, a piece of ground is chosen just about the level of high tide; it may be several acres in extent. The chosen ground is levelled, divided in basins and puddled. That is to say, the basins are covered with clay, which is trampled down, to prevent the water running away into the earth. Each basin is a little smaller than the one before it. It is also a little shallower, and a little lower. The object is to have the sea-water flowing very slowly from basin to basin. The basins are made progressively smaller because the solution takes up less and less room as the water evaporates. The evaporation proceeds rapidly in the warm Mediterranean climate, and the solution becomes more and more concentrated as it flows on. After a time it becomes saturated with the less soluble salts, and these begin to settle to the bottom. The first to come down are calcium carbonate, ferric oxide, and copper sulphate. These deposits are dredged out with wooden scoops, and the solution flows on to lower basins.

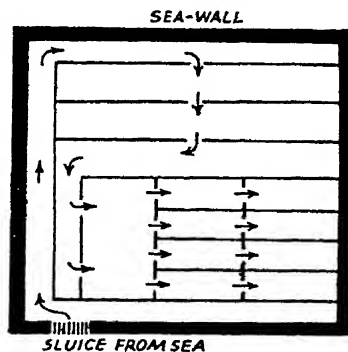


FIG. 12

More than nine-tenths of the water has to evaporate before the solution is saturated with sodium chloride. This salt, as we have seen, forms about four-fifths of the whole amount of dissolved solid. It is dredged out and left in heaps at the side of the basin. Water drains away from the heaps, and more soluble salts are washed out by rain. The less soluble sodium chloride is left, though there is, of course, some loss even of this.

Grey Salt

However carefully the scooping out is done, there is always some clay taken up with the salt. This clay gives the salt a grey appearance. For this reason sea salt is called *sel gris*, that is, grey salt. The amount of insoluble matter may be as much as a sixth of the whole mass.

We can get rid of the unwanted clay. The grey salt is dissolved in fresh water, and left to settle in a concrete basin. Then the clear liquid is run off, and the salt recrystallized.

Merchants were known to purify and recrystallize grey salt in this way, and so obtain a good price for it. If they were dishonest, they would then sell the worthless lees at a lower price. The salt that had lost its savour, of which Jesus spoke, was this worthless stuff.

The *mother liquor*, as it is called, still contains valuable, and very soluble, salts, after most of the sodium chloride has been removed from it. Amongst these very soluble salts are salts of magnesium and potassium. These salts can be separated out by still further concentrating the solution.

Salt Deposits

There are numerous deposits of salt in various parts of the world, and there seems to be good evidence that these are the results of the drying up of ancient seas and salt lakes. The evidence amounts to this: the arrangement of the salts in the beds is very much the same as that which occurs in artificial evaporating pans. Thus in the famous Stassfurt deposits, near Magdeburg in Germany,

the lowest layers contain sodium chloride and other deliquescent chlorides. Above these are layers containing potassium and magnesium sulphates, and in the uppermost layers are potassium and magnesium chlorides, which are very soluble. It has been estimated that a sea or salt lake would have to be $12\frac{1}{2}$ miles deep to produce such deposits. That does not seem to be an impossibility, even though it is improbable. The Dead Sea, with its Ridge of Sodom, suggests another solution of the problem. A thick deposit may have formed, and then been washed down into a shallower sea, so that beds of salt were formed in stages, without the necessity of an improbably deep sea.

The most famous of all salt deposits are those at Wieliczka, near Cracow in Poland. The mass of salt in this region has been estimated as being 900 miles long and 20 miles wide. The thickness of the beds is about 400 yards, and that does take some explaining. There would have to be a sea 900 miles long and 20 miles wide. If it had the original salinity of the open ocean, say 35 ounces of salt per cubic foot, it would have to be at least 10 miles deep across the whole area:

A cubic foot of water weighs 1,000 ounces.

Taking the density of salt as roughly $1\frac{1}{2}$, 35 ounces of salt is equivalent to about 24 ounces of water in volume.

So we have the depths:

1,000 units of water: 24 units of salt

50,000 feet of water: 1,200 feet of salt

which gives us water about 10 miles deep.

Such a salt sea seems highly improbable. The analogy of Kara Bogaz on the Caspian Sea suggests a more likely explanation. If a sufficiently shallow entrance allowed water to pour in continuously from the ocean, then the depth of the sea need not have been much more than 400 yards.

The mines at Wieliczka have been worked for about 700 years. A whole village was carved out of the salt at the lower levels, and here many of the miners lived.

Solutions of Gases

Gases dissolve in water, and some of the solutions are both interesting and important. The chapter on carbon dioxide shows how vitally important is the solution of carbon dioxide in water.

The solution of ammonia in water is interesting largely because of the high solubility of the gas. Water dissolves no less than 700 times its own volume of ammonia at room temperature. There is an exciting experiment which illustrates the remarkable solubility of ammonia.

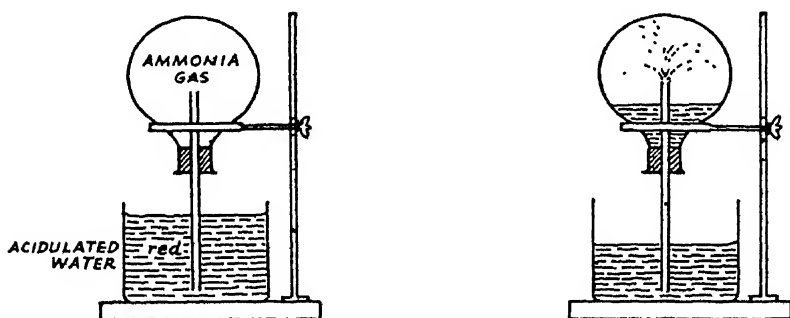


FIG. 13

A large glass vessel is fitted on the underside with a narrow tube and a stopcock. The vessel is filled with ammonia gas. It is placed on a stand with the tube running down into a supply of acidulated water sufficient to fill the vessel.

The stopcock is opened, and the water at once begins to creep up as it dissolves the small amount of ammonia in the tube. The water reaches the top of the tube and begins to spill over into the vessel. The creep becomes a rush, and then a furious rush. The first water that enters the vessel dissolves up to 700 times its own volume of ammonia. A partial vacuum is thus created in the vessel, and water is forced up through the narrow tube by outside air pressure.

To add a touch of colour to a very spectacular experi-

ment, the supply of water below may be tinted with red litmus. As soon as the water dissolves the ammonia it becomes alkaline, and the red litmus changes instantly to blue.

The *liquid ammonia* sold in shops is not liquid in the ordinary sense. It is a solution of ammonia in water. It is used in household cleaning to counteract unwanted acids.

Oxygen in Water

The most important of all gaseous solutions is the solution of oxygen in water. Upon this solution depends the existence of fish life. The gills are able to take dissolved oxygen from the water that flows through them.

We sometimes use the derogatory expression, 'He drinks like a fish', when we mean that someone is drinking more than is good for him. And fishes certainly do seem to be gulping down a lot of water. Actually they are breathing. They take in water and pass it back through the gills, and thus keep up the supply of oxygen that is necessary to life.

Amphibians (frogs, toads, and newts) are so called because they can, at different stages of their lives, breathe both dissolved oxygen and atmospheric oxygen. In the tadpole stage they are supplied with gills for breathing dissolved oxygen. The gills fade away and are replaced by lungs. When they reach this stage tadpoles have to come to the surface frequently for gulps of air.

When we boil water we boil the dissolved air out of it. The air bubbles which form, before they rise to the surface, do not look like steam bubbles; they do not collapse or burst in the same way. All the air does not boil out of the water at once, but if we let the water go on boiling, all the air is eventually lost. Tea made with water that has been boiled too long is flat and unpalatable. The water should be boiled quickly, and used as soon as it boils.

Water boiled and then cooled would be useless for fish. They would drown in it because it does not contain usable oxygen. But if it were shaken up vigorously with air it would once more be suitable for fish to inhabit.

Sometimes, on very hot days, fish in shallow ponds put their noses out of the water. They are trying, in vain, to make do with atmospheric air as a substitute for the dissolved air the water has lost in the heat of the day. Water-weeds have a double use in aquaria and ponds. They take carbon dioxide from the water, and they give out oxygen; they remove the waste product, and supply the vitally necessary oxygen.

There is a very interesting point about the solubility of oxygen. The solubility is not very great; it is 3 volumes of oxygen to 100 volumes of water. This appears to be sufficient for fish, but there is evidently no superfluity. Here, as so often, life runs on a small, but adequate, margin. On the other hand, the low solubility of oxygen prevents that gas being removed from the atmosphere. If oxygen had a solubility approaching that of ammonia it would all be dissolved.

Solutions and Crystals

We commonly observe that solids dissolve much more readily in hot water than in cold. This is not always the case. Common salt, for example, dissolves almost as readily in cold water as in hot. But it is certainly the case with sugar, and saltpetre, and many other solids. They dissolve most readily in hot water.

Suppose we make a saturated solution of saltpetre; we dissolve as much as possible in hot water and we let the water cool. Cold water can hold much less saltpetre in solution than hot. The superfluous solid therefore comes down as crystals. This is indeed one way of forming crystals.

We shake up saltpetre in half a test-tube of water. If necessary we add more saltpetre; for we want some to be left after shaking. We warm the solution to dissolve the remainder of the saltpetre. We cool the solution rapidly by holding the test-tube under the cold tap. A mass of tiny crystals forms.

We heat the solution once more, and allow it to cool slowly. The crystals are decidedly bigger. We leave the test-tube overnight, to allow it to cool very slowly through

the last few degrees down to room temperature. Next day we find crystals at the top which are noticeably bigger than those below.

For much bigger crystals we rely, not on the slow cooling of a solution, but on the much slower evaporation of the water in a solution. We stir up saltpetre in a jar of lukewarm water. We stir very thoroughly, so as to have a saturated solution, and there should be a little undissolved solid. We pour the clear liquid into another jar, and leave it till next day. Once more we pour the liquid into another jar. We pick out a few of the best-formed crystals and return them to the solution. We put the jar in a place where it will not be disturbed, and where there are not likely to be great changes of temperature. The water slowly evaporates, and the crystals grow in size. This is not unlike the method by which salt is obtained from seawater.

The above methods often produce quite good crystals, but they are rather haphazard. A sudden rise of temperature would probably cause uneven solution of the crystals. With the necessary facilities we can achieve much better results. A warm, saturated solution is placed in a thermostat, and subjected to prolonged, carefully controlled, cooling. The liquid is completely enclosed so that evaporation cannot take place. By this means, large, perfectly-shaped crystals may be obtained.

Delayed Crystals

Crystals do need something to get them started. When we form saltpetre crystals in a test-tube there is plenty of disturbance, and once started the crystallization goes on.

But if we use quite clear water for the solution, and if we arrange things so that the concentration of the solution proceeds slowly and regularly, we may obtain a supersaturated solution, that is, a solution which contains more than the normal amount of dissolved solid. When crystallization is once started in a supersaturated solution, it proceeds rapidly until all the extra solid comes down as crystals.

Delay in crystallization is sometimes a nuisance. One

method of hastening it is to 'seed' the solution with small crystals of the dissolved material. That is what we do when making large crystals of saltpetre.

It is now possible to start crystallization by means of a beam of ultrasonic waves, that is, air waves of greater frequency than sound waves. These waves disturb the liquid, and so start crystallization. This has two advantages over other methods. The disturbance is very slight; and the waves can be directed to that part of the liquid where it is desired that crystallization should start.

Two Kinds of Solvent

There are two important classes of liquids which act as solvents. Water is typical of one class, and benzene of the other. There are indeed other kinds of solvent. Mercury, for example, dissolves metals to form amalgams. But such solvents are of minor importance beside the water and benzene classes.

Here is an example of the difference between the two kinds of solvent:

Water dissolves about a quarter of its own weight of sodium chloride.

Benzene dissolves about one ten-thousandth of its own weight of sodium chloride.

On the other hand:

Benzene dissolves three-quarters of its own weight of naphthalene.

Water dissolves less than a millionth part of its own weight of naphthalene.

The molecules of liquids of the water class include the hydroxyl group, OH ; water itself is HOH . These molecules have a strong attraction for one another. The molecules of liquids of the benzene class do not include hydroxyl, and they have very little attraction for one another.

Alcohol includes hydroxyl, and it belongs to the water class of solvents; ethyl alcohol is $\text{C}_2\text{H}_5\text{OH}$. Water and

alcohol mix in any proportions because all the molecules contain hydroxyl, and attract one another.

Benzene mixes with liquids of its own class because the molecules have no particular attractions, and therefore they can wander about freely.

But when water and benzene are shaken up together, and then allowed to stand, the water molecules, attracted to one another, come together and squeeze out the molecules of benzene. And so the two liquids separate, the lighter benzene floating on the heavier water.

The same sort of thing happens when we try to dissolve naphthalene in water. Though it is a solid, naphthalene is the same sort of substance as benzene. The water molecules come together, and do not mingle with the naphthalene molecules. But benzene and naphthalene molecules can mix indiscriminately, and so we get a solution of naphthalene in benzene.

Liquids of the benzene class include toluene, xylene, petrol, paraffin, carbon tetrachloride, and many others.

IV

CARBON DIOXIDE

1. What are the 'products of combustion'?
2. When is carbon dioxide poisonous? Why?
3. Why is carbon monoxide very poisonous?
4. Why do atmospheric gases not arrange themselves in layers?
5. What are the Valley of Death and the Grotto of Dogs?
6. What is the solubility of carbon dioxide?
7. What is soda-water?
8. How is sparkling wine made?
9. What is baking-powder?
10. How is carbon dioxide introduced into bread?
11. Why is carbon dioxide necessary to life?
12. What is photosynthesis?
13. What kind of atmosphere has Venus?
14. From what sources do plants take carbon dioxide?
15. How does carbon dioxide circulate?
16. How do calcium carbonate and bicarbonate differ?
17. Why are limestone rocks pitted?
18. How are limestone sink-holes and caves formed?
19. Which is the greatest of all caves?
20. How are stalactites formed?
21. How does the sea help to keep a balance in the supply of carbon dioxide?
22. How has man changed the carbon dioxide content of the air?
23. How does carbon dioxide affect climate?

CARBON dioxide is a vitally important gas. It is one of the prime necessities for life.

The carbon dioxide molecule (CO_2) consists of one atom of carbon united to two atoms of oxygen. We can therefore produce the gas by burning carbon in air, or more fiercely in oxygen.

Most of the things we use as fuel contain both hydrogen and carbon, and so we are apt to get water and carbon dioxide when fuel burns. This occurs so commonly that water and carbon dioxide are sometimes called 'products' of combustion'. Wood, peat, coal, oil, paraffin-wax, coal-gas, and other fuels give out these two products when they burn.

Is Carbon Dioxide Poisonous ?

Carbon dioxide is constantly being produced in our bodies by the slow combustion of fuel foods, especially starch, sugar, and fat. If it were poisonous, in the form in which it exists in our bodies, we should all be poisoned. Obviously it is not. However, it is an unwanted product. We get rid of it by breathing it out. Expired air contains from $3\frac{1}{2}$ to $5\frac{1}{2}$ per cent, by volume, of carbon dioxide.

But that is not a complete answer.

We certainly could not live in an atmosphere that was all carbon dioxide. We should be suffocated for lack of oxygen. But that does not answer the question either. Desdemona's life was brought to an end by means of a pillow. This was not because the pillow was poisonous ; it was merely a way of shutting off the supply of oxygen. Men sometimes drown, not because water is poisonous, but because it shuts off the supply of oxygen to the blood. Fish do not drown because they have special apparatus, the gills, for using the oxygen that is dissolved in water.

An atmosphere of the entirely harmless nitrogen would do equally well to suffocate a victim. Indeed, I seem to remember a story of Edgar Wallace in which an all-but-perfect murder was committed by surrounding the victim with an atmosphere of nitrogen.

What happens when we have an atmosphere between the two extremes of 100 per cent carbon dioxide and the

0.04 per cent of carbon dioxide in the air we normally breathe? Suppose we have an atmosphere consisting of: oxygen, 20 per cent; carbon dioxide, 20 per cent; nitrogen, 60 per cent. There is the same percentage of oxygen as in ordinary air, so apparently the victim is not being deprived of oxygen. Nevertheless, such an atmosphere would be quickly fatal. In this proportion carbon dioxide is poisonous.

The Chemistry of Breathing

The reason is not far to seek. Carbon dioxide is carried to the lungs from all parts of the body where it is produced, by the blood. The red corpuscles of the blood contain a red substance called *haemoglobin* (*haemo* means 'blood'). Carbon dioxide forms a loose compound with the haemoglobin, and so it is carried along. The capillaries (hair-like blood-vessels) of the lung have very thin walls. The carbon dioxide diffuses through these thin walls into the air spaces of the lungs, and is breathed out. It is replaced by oxygen, which also forms a loose compound with haemoglobin, and the oxygen is carried to all parts of the body. Now, if the air in the lungs already contains sufficient carbon dioxide, the outward diffusion of the gas does not take place. The haemoglobin is not available for oxygen-carrying, and the victim is, in effect, suffocated. The proportion of oxygen in the air that is breathed in does not seem to matter, so long as it is not unduly low. The proportion of carbon dioxide does matter.

The effect of carbon monoxide is rather different. It forms a more stable compound with haemoglobin, so that any haemoglobin with which it comes in contact is temporarily put out of action. For this reason the monoxide is poisonous in much smaller concentrations than the dioxide. It is not, however, a cumulative poison; if recognized in time its effects are readily overcome.

I have a report of two fatal accidents caused by people shutting themselves up in small rooms with gas-fires burning, to try to keep warm in very cold weather. At least three things would contribute to the accidents:

(i) The supply of oxygen would be seriously reduced by the fire, as well as by the breathing of people in a crowded room.

(ii) The amount of carbon dioxide might be increased beyond the poisoning point.

(iii) In an atmosphere deficient in oxygen, the gas might be imperfectly burned and become carbon monoxide.

All three conditions would reduce the supply of oxygen to the body, and would promote suffocation.

A Heavy Gas

Carbon dioxide is a heavy gas, compared with other gases of the atmosphere. It is rather more than half as heavy again as air.

We know how liquids sometimes arrange themselves in layers, the heavier liquid below, with the lighter above. We may, for example, have mercury below, water above it, and oil above the water. These three liquids form distinct layers. But this only happens when the liquids do not mix. Water and alcohol, which are good mixers, do not arrange themselves in sharply separated layers.

Now, all gases mix. Each gas in a mixture of gases spreads out to fill the available space. That is why even a small escape of coal-gas can be smelt at a distance. And that is why the atmosphere does not settle down in layers: the heavy carbon dioxide below, lighter oxygen above it, and still lighter nitrogen above the oxygen. The air is a complete mixture of the many gases that compose it, so that a sample of air taken in one place has very much the same composition as samples taken elsewhere.

Nevertheless, carbon dioxide is so heavy, compared with air, that when it is produced in large quantities it may hang about in a dangerous, suffocating layer near the ground, before it disperses harmlessly.

When lime-kilns are burning, a large amount of carbon dioxide pours out. On a cold day the atmosphere near the kiln may seem pleasant; it is warm and drowsy.

But it would be dangerous to lie down and fall asleep near the kiln; one probably would not wake up again.

Valley of Death

There is in Java a famous and ill-omened Valley of Death. It is a deep, wooded valley, and from the bottom of it enormous quantities of carbon dioxide pour out, and hang about in a suffocating layer. Tigers, deer, and wild boar take refuge, as they imagine, in the sheltered valley. And they are quickly suffocated. Even men sometimes lose their lives in this valley, if they are rash enough to venture there.

Italy has the Grotto of Dogs. In this cave a large amount of carbon dioxide pours out, and hangs about near the floor of the cave before it disperses. As the name suggests, it is a poor place for dogs. Dogs breathe at a low level, so that they may very well be smothered by the gas if they wander into the cave; whereas men, whose breathing apparatus is a few feet higher, are safe enough.

In the Eifel district of South-west Germany there is an old crater lake called the Laacher See. Round about it there are openings from which carbon dioxide pours out. The district is not anything like as dangerous as the lurid and spectacular Valley of Death. It kills, not tigers, but insects, sometimes mice, and occasionally birds. When there is a dead calm the heavy gas hangs about over land and lake, and it is then advisable to keep away.

A Very Soluble Gas

Carbon dioxide is very soluble in water. Water appears to dissolve its own volume of the gas. This is independent of the pressure. If we have the gas under a pressure double that of the atmosphere, its volume is halved, and therefore its density is doubled. Water would therefore dissolve twice the weight of this very heavy gas. If pressure is once more reduced to ordinary atmospheric pressure, the extra carbon dioxide begins to bubble out into the air, and we get a rapid effervescence, which soon begins to fade away.

Hence soda-water. This is simply ordinary water

which has been charged with carbon dioxide under considerable pressure; the closed bottle preserves the pressure. When a bottle of soda-water is opened we get very rapid effervescence as the gas escapes. But the effervescence soon dies away, and the soda-water becomes flat. In order to be palatable it has to be drunk soon after the bottle is opened.

Many of our drinks are made palatable by the same means, that is by charging them in some way with carbon dioxide under pressure. When the gas has gone the drink is like spent soda-water, stale, flat, and unpalatable.

The bubbling sparkle in many drinks comes from carbon dioxide produced in the process of fermentation. This gas has to be conserved by keeping the liquid under pressure. It is usually sealed up in barrels or in bottles, which prevent the escape of the gas until they are opened.

Sparkling wines, of which champagne is the chief, are made in a special way. Still wine is made first, by the usual process of fermenting grape juice. Extra sugar is added to this still wine, and it is then bottled. The added sugar ferments, more carbon dioxide is produced, and the pressure in the bottles goes up to four or five times that of the atmosphere. The processes have to be carried out with great exactness, so that the pressure may be exactly right. If it is too high the bottles explode. The pop that is heard when a champagne cork is drawn, is caused by the sudden escape of high-pressure carbon dioxide.

It is said that inferior champagne is made by injecting carbon dioxide under pressure into ordinary still wine. Though it may be sold at a high price, such wine has nothing to commend it.

Carbon Dioxide in Food

It is not only drinks that are made palatable by carbon dioxide. We also depend on this gas in baking.

An ordinary piece of dough made of flour and water and a little salt, and baked, would be a hard, and almost uneatable, mass. To get any sort of satisfaction out of it we have to lighten it by fluffing it up in some way with small bubbles of carbon dioxide.

A common way of raising dough is to mix baking-powder with the flour before wetting it. The baking-powder is a mixture of an acid substance with an alkali; usually some starch is added to the mixture. A usual mixture is two parts of cream of tartar to one part of bicarbonate of soda (often called baking-soda, to distinguish it from the carbonate, which is washing-soda). The effect of the acid cream of tartar is to release carbon dioxide from the bicarbonate. This occurs especially when the dough is being heated in the oven. The bubbles of gas fluff the dough, and the resulting spongy bread is usually quite palatable.

In making loaves of bread, yeast and sugar are commonly employed to supply the bubbles of carbon dioxide. Some bakers inject the ready-made gas into the dough, a method which parallels the making of soda-water.

Solid Carbon Dioxide

We know that every gas has a certain critical temperature above which it will not liquefy, no matter how great is the pressure upon it. The critical temperature of carbon dioxide is rather high, 31°C . or 88°F ., so the gas is comparatively easy to liquefy. It does not liquefy at all at atmospheric pressure, but it does liquefy with moderate cooling and moderate pressure.

It is not difficult to freeze carbon dioxide. The production of solid carbon dioxide is now quite an important process. The solid is commonly called *dry ice* because it sublimates without changing to a liquid, and so does not leave a wet mess. It is the most convenient means of transporting carbon dioxide; liquid carbon dioxide has to be carried in expensive pressure containers.

Ice-cream makers, bakers, brewers, and many others find dry ice a great convenience.

The Mechanism of Life

Carbon dioxide certainly adds to the amenities of life. But its real importance lies in its function as part of the mechanism of life, that is, of the mechanical and chemical conditions in which life can exist.

There is a small proportion of carbon dioxide in the atmosphere. The amount is three or four parts in ten thousand. That may seem very small, but we have to remember that there is a vast weight of atmosphere about the earth. Over every square inch of the earth's surface there is nearly 15 pounds of atmosphere.

It is quite a simple calculation to find the weight of carbon dioxide. The area of the earth is 200 million square miles. To change to square feet we multiply by 5,280², and to change to square inches we multiply by 144. So the area is:

$$200 \times 10^6 \times 5,280^2 \times 144 \text{ square inches} \\ = \text{about } 8 \times 10^{17} \text{ square inches.}$$

We multiply by 15, because there are 15 pounds per square inch, and divide by 2,240 to bring it to tons.

$$= \frac{8 \times 10^{17} \times 15}{2240} \text{ tons} \\ = 5 \times 10^{15} \text{ tons}$$

We now want 4 ten-thousandths of this for the weight of carbon dioxide, and that is:

$$2 \times 10^{12} \text{ tons} \\ = 2 \text{ million million tons.}$$

In addition to the large amount of carbon dioxide in the atmosphere there is also a comparatively large, and very variable, amount in the soil.

Vegetables First

The primitive and fundamental kind of life is vegetable life. Plants can live solely on inorganic salts, water, and carbon dioxide. Indeed there is a common school experiment in which plants are grown with their roots in a solution of salts which contains all the elements that are necessary for growth. The plants are left to draw their own carbon dioxide from air and water. Such mineral food is useless to animals. What they require is organic

food which they obtain when they live on plants or other animals as food.

Besides turning inorganic materials into organic compounds, plants also manufacture starch. That is where carbon dioxide comes in. Plants have a double supply of the gas. Through the pores of their leaves plants take in carbon dioxide from the air. The water which moistens the soil contains large quantities of dissolved carbon dioxide, and this enters the plants through the roots. The simple molecules of water and carbon dioxide are the raw materials out of which plants manufacture the elaborate molecules of starch.

The plant must have a supply of energy to enable it to manufacture starch. It derives this energy from sunlight. For this reason the process is called *photosynthesis*, that is, putting together, or building up, under the influence of light. When it is in the dark, a plant behaves very much like ourselves in the matter of breathing. It breathes out water and carbon dioxide, and it does not manufacture starch. The colouring matter of green plants, chlorophyll, appears to act as a catalyst for the manufacture of starch.

The elaborate molecules of starch are composed of the three elements carbon, oxygen, and hydrogen. Oxygen and hydrogen are present in the starch molecules in the same proportions in which they occur in water: two volumes of hydrogen to one volume of oxygen. That is not to say that they occur as water, in the loose combination that is found in many crystals. The two elements are parts of an elaborate molecule, and are linked up in various ways to carbon atoms and to each other.

It appears therefore that the water molecules contain all the oxygen and hydrogen needed for building up starch molecules. All that is required from the carbon dioxide molecules is their carbon. The unwanted oxygen must be ejected. But not necessarily from the carbon dioxide; indeed, there is evidence that it is oxygen from the water molecules that is ejected. That is why green plants give out oxygen whilst light is promoting the manufacture of starch.

Oxygen of the Air

Oxygen links up so readily with other elements, that it is rather surprising to find so much free oxygen in the air, especially as the rocks of the earth's crust are incompletely oxidized—they could join with more oxygen. The release of free oxygen by green plants offers a reasonable solution of the problem. In its primitive state the atmosphere probably contained much less oxygen and rather more carbon dioxide than it does now. Green plants absorbed water and carbon dioxide, retained carbon and the elements of water, and gave out oxygen.

This idea seems so reasonable that the existence of free oxygen in the atmosphere of a planet would probably be accepted as evidence that green plants existed on the planet, especially if the quantity of oxygen was comparable with that on the earth.

The green grass and green leaves achieve two things necessary to animal life. They manufacture starch, and they turn inorganic salts into organic compounds suitable for animal food. Cattle, horses, zebras, giraffes, deer, antelopes, and other herbivorous animals feed on the starch and other organic foods thus provided. Carnivores prey on the herbivorous animals. And so we have the whole of vegetable and animal life ultimately dependent on water and carbon dioxide.

Carbon Dioxide on Venus

In these days of talk about space-ships, Venus, our nearest neighbour amongst the planets, seems almost next-door to ourselves. And there is therefore considerable interest in what conditions on Venus might be. It is sometimes said that scientists and science-fiction writers have no imagination. It is perhaps nearer the truth to say that they discipline their imaginations. They do not usually, for example, imagine life in impossible surroundings. They supply conditions somewhat similar to those of our own planet. H. G. Wells supplied his eccentric moon with an atmosphere, in order to make life there a possibility. We cannot conceive of animal and

vegetable life apart from water and carbon dioxide, for the simple reason that life without these essentials is not within our experience. Scientific imaginings therefore are adaptations or exaggerations of reality. When we abandon reality, we approach the realms of sheer nonsense, which is something scientists and science fiction-writers usually try to avoid, though not always successfully.

There is evidence which points to the fact that the atmosphere of Venus consists largely of carbon dioxide, heavily laden with dust. The planet has at least one of the requirements of life. But there appears to be no water and no free oxygen. That seems to be conclusive evidence that there are no green plants, or plants of any kind. And if there are no plants there are no animals.

People who object to that conclusion would have to discover chemical reactions that would make another form of life possible. And in this, disciplined imagination offers no help at all. The available evidence declares that there is no life possible on Venus.

Carbon Dioxide in the Soil

Living plants, and only living plants, can synthesize starch from carbon dioxide and water. As soon as the directive force of life departs, the creative faculty of the plant ceases. We then get the ordinary chemical reactions by which the elaborate organic molecules break down into the simple products of combustion. Water and carbon dioxide are the most important products of decaying vegetable matter. The oxygen driven out during starch manufacture has to be replaced by oxygen from the air or from the soil.

We may note in passing that fruit is sometimes preserved by 'gas storage'. That is to say, it is kept in an atmosphere of carbon dioxide and it keeps well in these conditions. The carbon dioxide keeps the fruit free from oxygen which is necessary as an oxidant in the process of decay.

Carbon dioxide is an important constituent of the soil. It forms sometimes a tenth of one per cent. Some of it

is absorbed into the roots of plants, in solution, and the plants use it in starch manufacture. It now seems certain enough that carbon dioxide in the soil is the main source from which plants draw their supply of the gas.

The proportion of carbon dioxide in the soil is very much higher than the proportion in the air. The proportion of carbon dioxide in soil air is often seven or eight times as great as in atmospheric air, and it may be much more than this. The proportion increases rapidly with depth. Measurements of the composition of soil air were made recently in a silty loam with a dense subsoil. In the first foot of soil, the percentage of carbon dioxide varied between $\frac{1}{4}$ of one per cent and $3\frac{3}{4}$ per cent. But at a depth of 6 feet the percentage of carbon dioxide was always more than 10 per cent. At the same time the percentage of oxygen in the soil air decreased from about 20 per cent near the surface to about 10 per cent at a depth of 6 feet. Some of the carbon dioxide in the soil is brought down from the atmosphere by rain. But a great part of it comes from the decay of animal and vegetable matter, especially if the soil is kept open to admit oxygen.

Darwin pointed out another use of carbon dioxide in the soil. It changes some of the insoluble materials of the soil into soluble carbonates, or bicarbonates, and so makes them available as plant food.

How Carbon Dioxide Circulates

There is a constant circulation of carbon dioxide:

(i) It is withdrawn from air and soil.

Green plants, under the combined impulses of life and light, take carbon dioxide from air and soil, especially from the soil. They use the gas in the manufacture of starch and other organic compounds.

Green plants, consisting largely of starch, are the food of herbivorous animals, and so the absorbed carbon dioxide becomes part of their bodies.

Carnivores prey on the herbivorous animals, and so the carbon dioxide reaches them.

Thus the outward circulation is to the bodies of all plants and animals.

(ii) It is returned to air and soil.

Dead animals and plants decay. The molecules of organic compounds oxidize, very largely into water and carbon dioxide.

Thus the carbon dioxide is restored partly to the air and partly to the soil.

It is the constant circulation of carbon dioxide, out into plants and animals, and then back into air and soil, that keeps the mechanism of life going. It is not, of course, the only thing that is necessary, but it is a highly important factor. The average time for a complete cycle, carbon dioxide moving outward and then back into air and soil, has been estimated at ten years, which is a surprisingly short time. Another, and shorter, circuit has been investigated in tropical forests. It seems that there is a short closed circuit, from the soil into the trees, and then back from decaying trees into the soil.

Carbon Dioxide and Lime

Carbon dioxide is closely associated with lime. Many hills and mountains owe their rounded beauty or proud elevation to the association.

The laboratory method of preparing carbon dioxide is simple and well-known. We merely pour dilute hydrochloric acid on pieces of chalk or limestone, or on marble chips. We might even use oyster shells. These varying substances—chalk, limestone, marble, oyster-shells—are chemically alike. They all consist, together probably with some impurity, of calcium carbonate, or carbonate of lime. The latter, rather old-fashioned name reminds us of the simple relation:

carbonate of lime = lime + carbon dioxide

In preparing carbon dioxide, the hydrochloric acid reacts with the lime to form calcium chloride, and the carbon dioxide is driven out.

We arrange the apparatus to collect the carbon dioxide in the most convenient way. The gas is so heavy that we can collect it by allowing it to pour down into gas-jars.

There are other ways of breaking up calcium carbonate into lime and carbon dioxide. We can, for example, heat the carbonate strongly. This is the method by which lime is produced in lime-kilns. The carbon dioxide pours out, and dissipates into the air.

Carbonate and Bicarbonate

Lime is one of the things that dissolve sparingly in water; only about a quarter of an ounce of it dissolves in a gallon of water. The solution is interesting, in spite of its weakness.

We shake up a little crushed lime with water, and so far as we can see it does not dissolve at all. We let the lime settle, and pour off the clear liquid into a bottle. This clear liquid, with a little lime dissolved in it, is lime-water. Although it looks no different from ordinary water, there is a difference. We pour a little lime-water into a jar, breathe into the jar, and shake up. When we have breathed into the jar several times the lime-water has a distinctly cloudy appearance; it looks as if a little milk has been stirred into it. That milky appearance in lime-water is the usual test for the presence of carbon dioxide. And incidentally we have shown that there is carbon dioxide in the breath.

We have actually reversed the process by which calcium carbonate is broken up into lime and carbon dioxide, that is to say, we have been putting together lime, in the lime-water, and carbon dioxide, in the breath, to form calcium carbonate. The carbonate is insoluble in water, so it forms tiny solid specks which give the milky appearance. Lime-water is always kept in tightly stoppered bottles. This is to preserve it from the small amount of carbon dioxide in the air, which would gradually change the lime to carbonate.

Instead of breathing into a jar containing lime-water,

we can get the milky appearance more quickly by blowing down a small tube into it. An interesting thing happens if we continue blowing down the tube: the milky appearance vanishes, and we have a clear liquid once more.

What happens is this. As more and more carbon dioxide from the breath is blown into the lime-water it unites with the carbonate to form calcium bicarbonate. The bicarbonate is soluble in water, and so it disappears into solution, and we get a clear liquid.

Calcium bicarbonate is not a very stable compound, it is readily split up into calcium carbonate and carbon dioxide. If we warm the liquid slightly the extra carbon dioxide is driven off, and the milky appearance returns. We can even displace the extra carbon dioxide by pouring the liquid from vessel to vessel. When we have done this a number of times the milky appearance returns.

There is still another way in which the bicarbonate can be readily changed to carbonate. Instead of removing the extra carbon dioxide we add more lime to unite with it, and thus we have a double lot of insoluble carbonate. All we have to do is to add lime-water to the liquid.

Some domestic water is very hard, and often this is because it has calcium bicarbonate dissolved in it. When this is so the water can be softened by adding lime to it. The bicarbonate is thus changed to insoluble carbonate. This can be allowed to settle, and the clear water run off. On a very small scale we can soften hard water by heating it in a kettle or pan. The deposited carbonate soon forms a crust on the pan.

Pitted Surface of Limestone

As rain falls, it dissolves some of the various gases of the air. In particular, it dissolves carbon dioxide, which is very soluble. So that rain, falling on limestone or on chalk, can change some of the carbonate to bicarbonate, and so dissolve it. There is not a great percentage of carbon dioxide in the air, so the amount which reaches limestone rocks is very small, and the change to bicarbonate is very slow. However, the change does go on

year by year, century by century, millennium by millennium. The amount of solution that is minutely small in a year, or even in a lifetime, may be enormous in the vast stretches of time we have to consider when chemistry touches on geology.

One effect of the solution of limestone is to give the rock its familiar pitted appearance. The amount of solution is very uneven from point to point on the rock surface. Water runs into cracks and hollows, and so increases the amount of solution at these points. Thus all the original unevennesses of the surface are exaggerated. That is the origin of the pitted appearance commonly seen on limestone rocks.

There is a very odd thing related of the nests of the white ant. These huge nests are built up of calcium carbonate. It is said that while the nest is alive with its great colony of white ants, the surface of the nest is smooth and unpitted. But when the white ants have died out, or abandoned the nest, the surface becomes pitted, like the surface of any other limestone. It may very well be that the presence of the living ants keeps the surface smooth. But there is another possible explanation. Abandoned nests are probably much older than inhabited nests, and so may show the pitted surface unobservable when it is new.

Sink-holes

Sink-holes are holes in limestone rocks into which streams sink. Usually they are high up on mountain slopes, and the streams which flow into them are small.

Sink-holes arise in this way. It may happen that there is a deep crack in a limestone rock. Water, with carbon dioxide in solution, trickles into the crack, slowly dissolves away the sides, and so widens and deepens the crack until it may become a large hole in the rock. That is not likely to happen unless there is trickling or running water. It is quite likely to happen when there is a crack in the bed of a stream. Cracks below the surface would be widened also, and they may become wide enough to take the whole stream. We then have a sink-hole, with

the river disappearing into it and following the underground passage it has dissolved in the rock. The river may run for a considerable distance through such an underground passage, and then reappear at the surface farther down its course.

Sink-holes and underground passages are common enough in limestone districts. There is a good example on the River Aire, in Yorkshire. This river rises in a small lake called Malham Tarn. A stream flows out of the tarn, runs for a few yards, and then disappears into a sink-hole almost blocked with lumps of limestone. Lower down the valley there is a high vertical cliff at Malham Cove. From the foot of this cliff, and near the middle of it, a stream runs out. But this stream is not a continuation of the stream which flows into the sink-hole. A party which investigated the matter, dropped into the sink-hole substances which could be detected in very weak solution. These substances were not detected in the stream at Malham Cove. But they were detected at Airehead, farther down the valley, where a stream bubbles up in the river-bed. Evidently the river had flowed through an underground passage from the sink-hole to Airehead.

Limestone Caves

Sometimes the change from carbonate to bicarbonate, and consequent solution of the rock, goes much farther. Passages are enlarged by solution until they become caves. Such caves are a common feature of limestone districts.

Sometimes a cave may be formed by solution, just below ground level. Then the stream may dissolve a way down to a lower level, and form a cave at this point. The upper cave is then left high and dry, without the river that had formed it. In a similar way a third cave may be worn out below the second, and there would then be two dry caves. The famous Mammoth Cave has no fewer than five sets of caves at different levels.

The Mammoth Cave is the greatest of all caves; it is in the limestone region of Kentucky. The galleries of this mighty cavern extend for a hundred and fifty miles, and

there is every variety of scenery to be seen when the ways are lit up. Some of the spaces in the cave are of vast size. One of them, called Chief City, has a vault 125 feet high over an area of 2 acres. The highest of them all is Lucy's Dome, which is 300 feet high. A number of rivers run through the cave. They meet in River Hall, where they form several lakes, before finding a way out into the open. It gives an idea of the immense size when we realize that in the rainy season the water of the lakes rises 60 feet above the low-water level. A feature of the Mammoth Cave is the deep pits, into some of which rivers plunge. Such pits, dissolved out by falling rivers, occur fairly commonly in limestone caves. Caves in the Pyrenees are famous for the extreme depth of such pits.

Dropping Wells and Stalactites

The small experiments we so laboriously carry out are sometimes performed naturally on a large scale, and with a sort of carefree abandon.

We have a small vessel containing a solution of calcium bicarbonate. We pour the solution from vessel to vessel, and after a time it takes on a milky appearance. The soluble bicarbonate has given up carbon dioxide, and become the insoluble carbonate. This experiment is carried out in nature on a large scale, large in both place and time; it goes on year after year.

The Dropping Well at Knaresborough, on the River Nidd in Yorkshire, is an example. Water containing bicarbonate of lime in solution drips down the face of a high rock into the river. Carbon dioxide is given up, and limestone is deposited on and about the rock face. People who like to accumulate curious things can usually obtain one at the Dropping Well. Various small objects, such as bird-cages, are hung up in the dripping water. After a time they have the appearance of being petrified, or turned to stone, as though Medusa had looked that way. In fact, they are covered with a deposit of calcium carbonate.

One of the most exciting features of limestone caves is the stalactites, long columns of rock which taper down-

ward from the ceiling of the cave. They may be at all stages of development, from tiny things to really massive ones. Somewhere in the cave water drips from a crack in the ceiling. Carbon dioxide is given up, and the carbonate is deposited about the opening. This begins a stalactite which gradually thickens and spreads downward.



FIG. 14

Some of the water, carrying calcium carbonate in suspension, drips to the floor, and deposits there a stalagmite. Stalagmites are usually broad and stumpy, as one might expect. They lack the tapering elegance of stalactites.

Stalactites grow slowly downward, and stalagmites grow still more slowly upward, till eventually the two meet. And so we may find complete columns. Usually these columns have pronounced waists where stalactite and stalagmite join. When a sufficient number of centuries has elapsed the waist may have filled up, so that we have a perfect column. The Mammoth Cave has a group of six such perfect columns. Each of them is 25 feet wide and 80 feet high.

If we look out for them, we may see tiny stalactites growing under bridges. They are small, because they have not been left for the centuries it takes for a large stalactite to grow.

Carbon Dioxide in the Sea

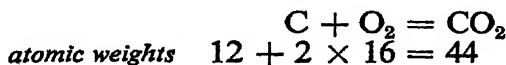
Carbon dioxide is so soluble in water that it is not surprising to find there is a considerable amount of it in sea-water. Estimates of the amount of carbon dioxide in the oceans seem to agree that it is very much greater than the amount in the atmosphere. Carbon dioxide

reaches the sea in various ways. Waves reach up, and snatch some of it from the air, along with other atmospheric gases. Some of it is brought down in solution by rain and rivers. Rivers also bring down calcium bicarbonate in solution, and this is another source of carbon dioxide. The sea contains an ample supply of the gas for the needs of sea plants and animals.

The sea seems, indeed, to preserve a balance of carbon dioxide, just as it helps to preserve a balance of temperature. In spring and summer, in temperate regions, there is a great increase in the growth of algae; as a result carbon dioxide is withdrawn from the water, and more is dissolved from the air. In autumn the deep waters well up from below, and bring carbon dioxide to the surface, and some of this extra gas goes to the air. Winds blowing north and south from tropical regions are rich in carbon dioxide; they help to increase the supplies in the depleted polar regions.

Carbon Dioxide from Coal

During the last half century there has been an enormous increase in the amount of coal burnt throughout the world. The carbon, which is the greater part of coal, is converted chiefly into carbon dioxide.



Thus the burning of 12 tons of carbon provides 44 tons of carbon dioxide. Every ton of carbon provides:

$$\frac{44}{12} = 3\frac{2}{3} \text{ tons of carbon dioxide}$$

A ton of ordinary, bituminous, coal contains about 16 hundredweight of carbon, and this would supply:

$$\frac{16}{12} \times 3\frac{2}{3} = \text{about 3 tons of carbon dioxide}$$

So the burning of thousands of millions of tons of coal would make no mean an addition of carbon dioxide to the atmosphere.

Measurements of the amount of carbon dioxide in the

atmosphere show that there has been a considerable increase:

Before 1900: 292 parts carbon dioxide per million parts other gases.

About 1935: 321 parts carbon dioxide per million parts other gases.

These measurements are by volume. They show that in the period 1900-35 there was an increase of about 10 per cent in the amount of carbon dioxide in the atmosphere.

This increase in atmospheric carbon dioxide is puzzling. Why has the ocean not dissolved most of the increase? It has been suggested that the cycle of increase of carbon dioxide in the air, followed by its solution in the sea, may fill rather a long period of time.

Carbon Dioxide and Climate

If we want to have a warm climate we should be producing carbon dioxide on an even vaster scale.

Carbon dioxide in the air has a greenhouse effect. It traps solar heat as a greenhouse does, though not quite in the same way. Solar heat passes through the air without heating it. It warms the ground and the air is then heated by the ground, so that we usually have the warmest air near ground level, and colder air as we ascend. Most of the heat is radiated away, again without warming the air, and so is lost to space. However, the molecules of water vapour, and especially those of carbon dioxide, absorb heat from the sun's rays, and so the atmosphere is warmed. More heat is absorbed as it is being radiated away, and so this loss of heat is reduced. This effect of water is readily observed. The weather on a clear summer day is hot. With a sky obscured by cloud it may be many degrees colder.

The presence of a lot more carbon dioxide in the air would result in a much warmer climate than we have at present. There appears to be no evidence that the earth ever had a much warmer climate than it has now. Even in the oldest sedimentary rocks there is evidence of glaciation. This is considered good evidence that the chemical

composition of the atmosphere has not varied very greatly since the world has been in its present form with a solid crust.

If for any reason the amount of carbon dioxide were greatly to be increased, and our climate became therefore much warmer, it is unlikely that the increase would last. More carbon dioxide would be brought down by rain, and much of it would go to the sea in solution. Some of it would be added to the solution of calcium carbonate, turning it to bicarbonate, and this also would go to the sea. Once more we should have the sea maintaining the balance of carbon dioxide.

It is possible that our present intensive production of carbon dioxide from coal may eventually lead to an increase in animal and vegetable life in the sea. Man has begun a new carbon dioxide cycle, and we do not know when it will end.

V

THE ELEMENTS

1. What is an element?
2. Why are sequences found in the properties of elements?
3. Which are the ultimate particles?
4. What are atomic numbers?
5. What are isotopes?
6. Which isotopes are found partially separated in nature?
7. Why are some atomic weights very different from whole numbers?
8. What is deuterium?
9. Which are the two kinds of heavy water?
10. Which rays come from radium? What are the properties of the rays?
11. What are the stages in the decay of radium?
12. What is meant by 'splitting the atom'?
13. What is meant by 'fission'?
14. What are the transuranium elements?
15. How does the cyclotron work?
16. What is the cause of an atomic explosion?
17. What is the hydrogen bomb?
18. Which colours are found amongst the elements?
19. What is the periodic table?

THERE are some substances that are easy enough to break up into simpler substances. We have seen that limestone can be split up into lime and carbon dioxide, merely by heating it to a cherry-red heat. Nothing appears to be added or subtracted in the process. Quite simply:

limestone \longrightarrow lime + carbon dioxide

Now it is possible, though not easy, to obtain from lime the two substances calcium, which is a rather soft white metal, and oxygen. We could obtain carbon and oxygen from carbon dioxide. There chemical analysis ends. These three substances—calcium, carbon, oxygen—are elementary.

The ores of iron are harder to break up, but we do get from them the element iron. Pure iron is iron and nothing else.

We pass an electric current through slightly acid water, and so split it into the two elements, oxygen and hydrogen, which can be simplified no further by chemical analysis.

It was formerly supposed that an atom of calcium was a minute particle of calcium, so small that it could be split no further. And so with the atoms of the other elements. Each was an ultimate particle, unrelated to atoms of other elements. The number of known elements was increased, until now we recognize 101 of them. According to the old idea we should have 101 different ultimate particles.

Sequences of Elements

Then it began to appear that the elements are not unrelated. There are groups of elements, with similar properties often running in sequences through the groups. There is the 'coinage group' of metals—copper, silver, gold. They all have melting points round about $1,000^{\circ}\text{C}.$, and they share the remarkable properties that make these three metals suitable for coins and medals.

There is the well-known group of halogens, or salt-forming elements. In studying this group of elements it

soon becomes clear that properties increase or decrease in intensity in order of the atomic weights:

fluorine 19	chlorine 35½
bromine 80	iodine 127

The melting points and boiling points of the halogens increase from element to element:

	<i>Melting point</i>	<i>Boiling point</i>
fluorine . . .	—223° C.	—188° C.
chlorine . . .	—107° C.	— 34° C.
bromine . . .	— 7° C.	59° C.
iodine . . .	114° C.	184½° C.

Deepening colour runs through the group of elements in the same order:

fluorine—light yellow
 chlorine—deeper yellow-green
 bromine—the gas is deep red
 iodine—almost black

The elements all form acids with hydrogen. These acids have similar chemical composition:

hydrofluoric acid—HF
 hydrochloric acid—HCl
 hydrobromic acid—HBr
 hydriodic acid—HI

The ways in which the elements unite with hydrogen also form a sequence:

hydrogen and fluorine—explode even in the dark
 hydrogen and chlorine—explode in the light
 hydrogen and bromine—explode when heated
 hydrogen and iodine—the reaction is not complete: there is always present uncombined hydrogen and iodine, as well as hydriodic acid

The alkalis—lithium, sodium, potassium—form another well-defined group. The alkaline earths—calcium, strontium, barium—are still another well-known group. The

rare-earth metals have properties so similar that it is difficult to separate them.

Atoms Have Structure

Not all properties fit in as neatly as those we have been looking at. But there is sufficient similarity to suggest that the elements are not a hundred or so unrelated materials. There must be some similarity of structure in the atoms to account for the multiplicity of similarities and gradations of properties. One or two similarities or gradations might be chance, but hardly the host of similarities and sequences that actually exist. And if an atom has a structure, if it is built up of things smaller than itself, then it is not one of the ultimate particles. We must pry deeper to find these.

The first of the ultimate particles to be discovered was the electron. This is a minute particle with a negative electric charge, and extremely small mass. Because of the charge, a stream of electrons can be deflected from a straight path, by electric and magnetic fields. The stream is deflected toward the positive pole, so we know that the charge must be negative. It was this deflection that led J. J. Thomson to his discovery of the electron.

Atoms cannot be exclusively composed of electrons. If they were, then any mass of an element would have a high negative charge. But we know very well that this is not so; usually there is no apparent charge. There must be a positive charge to balance the negative charge of the electrons, and so to counteract its effect. Lord Rutherford showed that the positive charge is concentrated on an extremely minute nucleus. He showed also that the charge is very roughly equivalent to double the atomic weight. We were given a picture of the atom as a sort of miniature solar system: the positively-charged nucleus, with negatively-charged electrons in orbits about it.

Atomic Numbers

Moseley demonstrated the effect of the nuclear charge quite definitely. He gave us the idea of atomic numbers,

and showed that the atomic number is the number of unit positive charges on the nucleus. The number of positive charges on a nucleus identifies the atom as an atom of a particular element. The number of charges increases, unit by unit, from 1 to 101. That is to say, there are 101 different elements, with the possibility of further elements with more than 101 charges on the nucleus.

When the roll of the elements was made up, by using the atomic numbers, the exact positions of a few gaps were shown clearly. These gaps have since been filled up, either by the discovery of the elements in nature, or by their artificial production. We now have a complete table of the elements:

1 hydrogen	2 helium	3 lithium
4 beryllium	5 boron	6 carbon
7 nitrogen	8 oxygen	9 fluorine

and so on, up to element 101 mendelevium.

Protons and Neutrons

The single positively-charged particle which is the nucleus of a hydrogen atom, is called a proton. It seemed at this stage that there were two, and only two, kinds of ultimate particle: protons and electrons. The minute proton contained all but a very small part of the mass of the atom; the electron contained little more than $\frac{1}{2000}$ of the mass. It seemed that the structure of the elements should be:

hydrogen: 1 proton, 1 electron
 helium: 2 protons, 2 electrons
 lithium: 3 protons, 3 electrons

If that were so, the atomic weights of the elements, taking that of hydrogen as unit, should be: hydrogen 1, helium 2, lithium 3, and so on. But a glance at the table of atomic weights shows that this is very far from being correct. The list, indeed, begins to the nearest whole number: hydrogen 1, helium 4, lithium 7. And uranium is not 92, its atomic number, but 238.

The possibility of additional electrons in the nucleus

was unsatisfactory, because there did not seem to be room for them in the minute nucleus.

The discovery of the neutron gave just what was wanted for a reasonable theory of the nucleus. As the name suggests, the neutron is a particle without charge of any kind, either positive or negative. Investigation showed it to have very nearly the same mass as a proton.

We have pointed out that an electron has a very small mass compared with that of a proton, so that almost the entire mass of an atom is in the nucleus. For the present purpose we can ignore the small mass of the electrons, and consider the mass of an atom as being the same as that of the nucleus.

Helium has an atomic weight of 4. The nucleus contains 2 protons, so there must also be 2 neutrons to make up the mass of 4. Proceeding in this way we find that the commoner nuclei of the lighter elements must be made up as shown in the following list:

		<i>Approximate atomic weight</i>	<i>Protons</i>	<i>Neutrons</i>
hydrogen	. .	1	1	0
helium	. .	4	2	2
lithium	. .	7	3	4
beryllium	. .	9	4	5
boron	. .	11	5	6
carbon	. .	12	6	6

Near the other end of the table is uranium, element 92, with an atomic weight of 238. The number of neutrons in the nucleus must be:

$$238 - 92 = 146$$

Isotopes

There are two points we should be quite clear about:

(i) The identity of an element depends only on the number of protons in the nucleus.

(ii) The mass of an atom is almost entirely in the nucleus. It depends on the total number of nuclear particles, both protons and neutrons.

We still have the idea that atomic weights should be whole numbers. This is certainly not correct. Some of them are far removed from whole numbers. We find, for example:

magnesium 24.32	chlorine 35.457
iron 55.84	dysprosium 162.46

That used to be called 'an unexplained anomaly'. The discovery of isotopes provided the explanation.

Lead taken from radioactive minerals was found to have varying atomic weights. These atomic weights were different from that of lead taken from other sources, and different from one another. There was one atomic weight for lead from uranium minerals, another for lead from actinium minerals, and still another for lead from thorium minerals. The material in each case was lead, with all the chemical properties of lead.

It appeared that an element might have different kinds of atoms. The number of protons in the nucleus had to be the same; if the protons differed, then the atoms would be those of other elements. But a variation in the number of neutrons would explain what had been observed: chemical similarity, and differences in atomic weight.

An atom may have a nucleus containing 12 protons; its atomic number is 12, and that marks it definitely as an atom of magnesium. But the nucleus may also contain 12, 13, or 14 neutrons, so that the atomic mass may be:

$$12 + 12 = 24; 12 + 13 = 25; 12 + 14 = 26$$

That is to say, we have three varieties of the magnesium atom. They are all alike in being magnesium atoms, forming exactly the same compounds with other atoms. But they have masses in the ratio:

$$24 : 25 : 26$$

These varieties of an element are called *isotopes* of the element. As a rule the isotopes of an element are chemically alike, except for some slight variations in properties that depend on mass: boiling point, and rate of diffusion

through a porous screen, for example. But the nuclear properties are completely different; the nuclei of isotopes behave differently in bombardment experiments.

The isotopes of uranium are U^{235} and U^{238} ; these are often written U 235 and U 238. The U 235 isotope forms only a small fraction of ordinary uranium. It was this isotope that was separated out with such excessive difficulty when the first atom bomb was being prepared. The difficulty was the result of chemical similarity. The necessity to separate it arose out of the difference in nuclear reactions, for U 235 was the only isotope that gave the nuclear reaction that was then desired.

Most elements have a number of stable isotopes. And in addition to these a large number of short-lived, radioactive isotopes have been prepared.

Mixed Isotopes

The existence of isotopes explains why some atomic weights are far removed from whole numbers. As a rule, a natural element is a complete mixture of its stable isotopes, always in the same proportions. Chlorine from the salt mines of Wieliczka, or rock salt in the Sahara, has the same atomic weight as chlorine from the Atlantic. In each case the atomic weight is the average of the masses of the isotopes.

Ordinary chlorine is a mixture of 76 per cent Cl^{35} , and 24 per cent Cl^{37} . 35 and 37 are the numbers of nuclear particles, protons and neutrons. The actual atomic masses are a little less than 35 and 37; they are 34.98 and 36.98. Here is the working out of the average:

34.98	36.98	2658.48
76	24	887.52
<hr/>	<hr/>	<hr/>
2448.60	739.60	3546.00
209.88	147.92	<hr/>
<hr/>	<hr/>	
2658.48	887.52	
<hr/>	<hr/>	

$$3546 \div 100 = 35.46$$

That is, allowing for approximations, near enough to the listed atomic weight of chlorine.

There seem to be few exceptions to the rule that a natural element is a complete mixture of its isotopes, always in the same proportions. When chemistry touches life we are apt to find peculiar things happening. Carbon has two stable isotopes, C^{12} and C^{13} ; C^{12} forms more than 99 per cent of ordinary carbon. Living organisms seem to have some preference for the lighter isotope. There is a higher percentage of C^{12} in the carbon of living things than in the carbon of limestone. Other slight differences have been observed, not always with any degree of certainty.

There is, however, one striking set of exceptions: the set which drew attention to the existence of isotopes. Lead is one of the end products of radioactive decay. The particular isotope which is produced depends on the original element from which it came. Ordinary lead is a complete mixture of: Pb 206, Pb 207, Pb 208, and a little Pb 204. Lead from the decay of uranium has a higher proportion of Pb 206 than ordinary lead. Lead from actinium has a higher proportion of Pb 207. And lead from thorium has a higher proportion of Pb 208.

The general rule about the mixture of isotopes shows that there must have been a very thorough mixing in the early stages of earth formation. The partial separation of the isotopes of lead in radioactive rocks is readily accounted for by the fact that this lead was formed after the original mixing. And some other elements must have been subjected to conditions that partially separated the isotopes. Gravity, diffusion, and life are three such conditions. There appear also to be well-established cases in which nuclear processes have occurred since the original formation of the elements.

The complete mixture of isotopes is not confined to the earth. It extends also to the samples of cosmic matter that come to us as meteorites. The example of potassium has been specially noted. Potassium has a radioactive isotope, K^{40} ; this isotope forms 0.12 per cent of ordinary potassium. It has been found that K^{40} forms the same

proportion of the potassium of meteorites. The rate of decay is the same in both cases, so however far back we go, there must have been equal percentages of K^{40} in the potassium of the earth, and in that of meteorites. There is thus a strong presumption that the potassium of the earth and the potassium of meteorites came into existence at the same time, and under the same conditions of mixing. That is a fact that should not be omitted in any consideration of the origin of the solar system.

Heavy Hydrogen

There is one isotope which stands out from all the others. This is heavy hydrogen, whose nucleus consists of one proton and one neutron, so that it has a mass of 2. Heavy hydrogen has, for this reason, been called *deuterium*, with the symbol D. Deuterium went undetected for a long period of chemical research, because it forms a very small fraction of ordinary hydrogen: one part in 5,000.

The hydrogen molecule consists of two linked atoms of hydrogen; the usual molecule is represented by H_2 . A molecule of deuterium may be D_2 , that is, two linked atoms of deuterium. But we may also have molecules of HD, that is, a deuterium atom linked to an ordinary hydrogen atom. HD molecules are far more common than D_2 molecules. If we think of a deuterium atom seeking a partner, it has 5,000 hydrogen atoms to choose from, and only one of these is a deuterium atom. There is just about 5,000 times as much HD as D_2 in ordinary hydrogen.

Just as there are two kinds of deuterium molecule, so there are two kinds of heavy water. There is the kind with D_2 instead of H_2 ; this is D_2O . And there is the kind with HD instead of H_2 ; this is HDO.

It is an interesting fact that HDO has been detected, by spectrum analysis, in the moisture of the atmosphere, but the much rarer D_2O has not been detected.

Heavy water does not, of course, have twice the weight of ordinary water, because the comparatively heavy

oxygen is the same in both. The comparative weights are:

$$\begin{aligned} \text{H}_2\text{O}: & 2 \text{ (for H}_2\text{)} + 16 \text{ (for O)} = 18 \\ \text{HDO}: & 1 \text{ (for H)} + 2 \text{ (for D)} + 16 = 19 \\ \text{D}_2\text{O}: & 4 \text{ (for D}_2\text{)} + 16 = 20 \end{aligned}$$

So that HDO has $1\frac{1}{8}$ the weight of ordinary water, and D_2O has $1\frac{1}{3}$ times that weight.

The great difference in atomic masses between ordinary hydrogen and deuterium makes it comparatively easy to isolate heavy hydrogen: compared, that is, with the extreme difficulty of separating the isotopes of other elements in sizeable quantities. The early method of isolating heavy hydrogen is of interest. When an electric current is passed through slightly acid water, the water is split into oxygen and hydrogen. The hydrogen which comes off may be either of the two isotopes; but compared with the amount of each in the water, the lighter isotope comes off five times as quickly as the heavier isotope. Thus, when half the lighter isotope has gone, only a tenth of the heavier isotope is gone. So it arises that the concentration of heavy hydrogen increases as electrolysis proceeds, perhaps for months.

Electrolysis alone does not produce pure heavy hydrogen. This can be obtained by allowing the gas to diffuse through a porous screen. The light gas diffuses more quickly, so the gas behind the screen has an increased proportion of heavy hydrogen. Repeated diffusions give practically pure heavy hydrogen.

There are now other ways of concentrating heavy hydrogen, though electrolysis is still an important method. It is carried out cheaply in Norway, where there is a vast amount of easily available hydro-electric power. D_2O is manufactured by the ton for use in atomic piles.

Rays from Radium

Elements at the heavy end of the table of elements are radioactive. That is to say, their nuclei are spontaneously breaking up. Usually the nucleus ejects a

single particle, and so becomes a nucleus of another kind of atom.

The best known of the radio-elements is radium, which is element 88. Radium, and the products which come from it, emit rays. In an electric field the rays are separated into three parts:

(i) Alpha-rays are deflected toward the negative pole; this shows that they are positively charged.

(ii) Beta-rays are deflected toward the positive pole; this shows that they are negatively charged.

(iii) Gamma-rays go straight out, without deflection. They have no charge at all.

Further investigation reveals interesting things about the three kinds of rays:

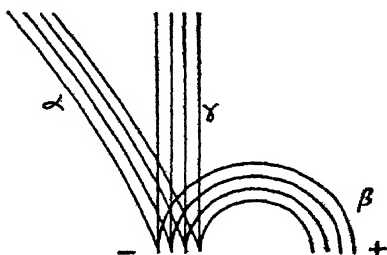


FIG. 15

(i) Alpha-rays are streams of positively-charged particles called alpha-particles. Each particle consists of two protons and two neutrons, so that it is a helium nucleus. These particles pick up stray electrons, and so become ordinary atoms of helium. For this reason helium is found in radioactive rocks.

(ii) Beta-rays are streams of electrons.

(iii) Gamma-rays are electromagnetic waves, like light waves of very short wave-length. When an atom has surplus energy it radiates it as gamma-rays. These rays have been used in the treatment of cancer; the unwanted alpha-rays and beta-rays are stopped by a screen.

Transformation of Radium

Radium goes through one transformation after another, until finally it is changed into substances that are not radioactive. It is rather fascinating to follow these changes, down and up in the table of elements.

When an alpha-particle is ejected the nucleus loses two protons and goes down two places in the table. It loses four units of mass—two protons and two neutrons.

When a beta-particle is ejected, this is done at the expense of a neutron. By losing the negative electron the neutron gains a positive charge and becomes a proton. The loss of a beta-particle gives the nucleus an extra proton, and so takes it up one place. The mass is unchanged; we have a proton instead of a neutron.

Now let us look at the changes:

(i) A radium nucleus ejects an alpha-particle. This takes it down two places, from element 88 to 86. It becomes a nucleus of radon, which is an inert radioactive gas.

(ii) A radon nucleus ejects an alpha-particle, and goes down from 86 to 84. It becomes a nucleus of radium A, which is an isotope of polonium (element 84).

(iii) A nucleus of radium A ejects an alpha-particle, and goes down from 84 to 82. It thus becomes a nucleus of radium B, an isotope of lead. This isotope is unstable, because it has too many neutrons in the nucleus.

(iv) A nucleus of radium B ejects a beta-particle, and thus changes one of the surplus neutrons to a proton. The nucleus rises from 82 to 83. It becomes a nucleus of radium C, which is an isotope of bismuth.

(v) A nucleus of radium C ejects an alpha-particle and almost instantly a beta-particle. One change up, and two down. That takes the nucleus back from 83 to 82. It becomes a nucleus of radium D, another unstable isotope of lead, with too many neutrons.

(vi) A nucleus of radium D ejects a beta-particle and so gets rid of another surplus neutron. This takes it up again to 83. It becomes a nucleus of radium E, which is an isotope of bismuth.

(vii) A nucleus of radium E ejects a beta-particle,

and off goes another surplus neutron. It goes up to 84, and becomes a nucleus of radium F, which is an isotope of polonium.

(viii) A nucleus of radium F ejects an alpha-particle, and so goes down two places to 82. It becomes a nucleus of radium G. Radium G is a stable isotope of lead; there is no longer a surplus of neutrons, so it is not radioactive.

The long series of changes from radium to lead is summarized in the following diagram:

<i>Element in table</i>	<i>Atomic number</i>	
radium .	88	Ra
francium .	87	↓ α
radon .	86	Rn
astatine .	85	↓ α
polonium.	84	RaA
bismuth .	83	↓ α
lead .	82	RaB

\nearrow^{β} RaC $\searrow^{\beta\alpha}$ RaD \nearrow^{β} RaE \nearrow^{β} RaF
 \searrow^{β} RaG

α and β indicate the particles which are ejected.

We can readily find which isotope of lead is represented by radium G. The loss of a beta-particle does not change the mass; it merely changes a neutron to a proton. The loss of an alpha-particle removes four units of mass: two protons and two neutrons. Altogether five alpha-particles are ejected. So we have:

	<i>Atomic weight</i>
radium	226
5 alpha-particles	20
	<hr/> 206

The lead in radium rocks is Pb 206.

Splitting the Atom

The particles ejected from the nuclei of radio-elements, are ejected at great speed, as much as ten thousand miles per second. For this reason they are admirable projectiles for bombarding the nuclei of other elements. Various

kinds of projectile are available. There are protons, which are the nuclei of hydrogen; there are deuterons, which are the nuclei of deuterium, one proton and one neutron; there are alpha-particles, which are the nuclei of helium atoms, two protons and two neutrons; and there are neutrons. Nowadays there are also heavier nuclei available for bombardment, especially the nuclei of C^{12} , N^{14} , and O^{16} . All these particles have positive charges, because of the protons, with the exception of the neutron, which has no charge. Neutrons are often used, in preference to other particles, for this reason. The nucleus is itself positively charged; it therefore repels other positively-charged particles; and a direct hit by one of these repelled particles is less likely than a hit by the uncharged neutron.

The nucleus of an atom is small in the extreme, even compared with the extremely small atom. If the whole atom were magnified to the size of a large hall, the nucleus would be no bigger than a bead. Aiming at the nucleus of an atom in the hope of registering a hit, is like aiming at a large hall in the hope of hitting a bead situated in some unknown part of the hall. It would be a hopeless proceeding, but for one thing: the bombarding projectiles are ejected in millions.

When a thin sheet of one of the elements, or of a compound, is being bombarded with millions of high-speed particles, we do get large numbers of hits on the nuclei. And when a nucleus is hit in this way some extraordinary things happen. One of the commonest of results is that a proton may be thrown out of the nucleus. And that, of course, changes the identity of the atom; it becomes an atom of an element one place lower in the table of elements. The old, alchemic dream of transmuting elements has been realized.

Changing the nuclei of elements by bombardment is what is known as 'splitting the atom'.

Fission

Uranium is one of the radio-elements. The nuclei of the atoms are breaking up spontaneously, so it might seem hardly worth while assisting the process of splitting,

by bombardment. Nevertheless, when uranium was bombarded, the result was sensational. Instead of losing a single proton, the atomic nucleus was actually split into two pieces of not greatly unequal size. Very roughly the nuclei were halved.

The first element to be detected amongst the products of the bombardment of uranium, was lanthanum, which is element 57. Barium, which is element 56, was also detected. If the nuclei had actually been roughly halved, there should be elements corresponding to $92 - 57 = 35$, and $92 - 56 = 36$, or at any rate somewhere near 35 and 36. Strontium (element 38) and yttrium (element 39) were detected. There was no doubt about the smashing of the nuclei.

It is rather a pity that the vigorous word 'split' should have been used for the process of 'knocking chips off the nucleus'. We now have the less vigorous word 'fission' for the more vigorous and sensational process of smashing the nucleus in two.

Transuranium Elements

The transuranium elements are elements with atomic numbers greater than 92, which is the atomic number of uranium. Nine of them are now known. They are:

93 neptunium (Np)	94 plutonium (Pu)
95 americum (Am)	96 curium (Cu)
97 berkelium (Bk)	98 californium (Cf)
99 einsteinium (E)	100 fermium (Fm)
101 mendelevium (Mv)	

Two of these elements, neptunium and plutonium, have been detected in uranium minerals. They are formed when uranium nuclei are acted on by stray neutrons. These two, as well as the other seven, have been formed artificially. The process of forming neptunium and plutonium is described in physicist's shorthand:

- (i) $\text{U } 238 + n \longrightarrow \text{U } 239 + \text{gamma-rays}$
- (ii) $\text{U } 239 \longrightarrow \text{Np } 239 + e^-$
- (iii) $\text{Np } 239 \longrightarrow \text{Pu } 239 + e^- + \text{gamma-rays}$

This is easy enough to interpret:

(i) A nucleus of U 238 captures a neutron (n). The number of protons is not changed, so it remains a nucleus of uranium. But the atomic mass is increased by one neutron, and becomes U 239. There is surplus energy, and this is radiated as gamma-rays.

(ii) U 239 ejects an electron (e^-). The loss of an electron changes one of the neutrons to a proton. The gain of a proton raises the nucleus to a nucleus of element 93, which is neptunium (Np). The mass remains at 239.

(iii) Np 239 ejects an electron. Another neutron is thus changed to a proton, and the gain of a proton raises the nucleus to a nucleus of element 94, which is plutonium (Pu). Again there is surplus energy, and this is radiated as gamma-rays.

It is by this series of processes that plutonium is manufactured. It is a different element from the others with which it is associated (not merely a different isotope of the same element), and so it can be separated out by chemical means.

Plutonium, like other elements of high atomic number, is radioactive, but the rate of decay is slow. Its half-life is about 20,000 years. That is to say, if an ounce of plutonium were manufactured now, and left to its own devices, at the end of 20,000 years our remote descendants would find half an ounce of it left. And their remote descendants, after another 20,000 years, would still have a quarter of an ounce. This slow decay makes it possible to build up a large stock of plutonium, provided the process of manufacture is on a large enough scale.

Speeding up Particles

When particles are charged their speed can be accelerated in an electric field. Positively-charged particles, including protons, deuterons, alpha-particles, and other positive ions, are attracted toward the negative pole, and the force of attraction accelerates them. Electrons, and negative ions are attracted to the positive pole, and so accelerated.

Neutrons cannot be accelerated in this way. They have no charge, so the electric field does not affect them. We have, however, means of obtaining swiftly moving neutrons. By one of these, beryllium powder is bombarded with alpha-particles, and it then ejects neutrons moving at high speed.

The cyclotron is an instrument for speeding up bombarding particles. It consists of two hollow conductors, 'a very large and shallow metal pill-box, cut in two along a diameter, and the edges separated'. The conductors,

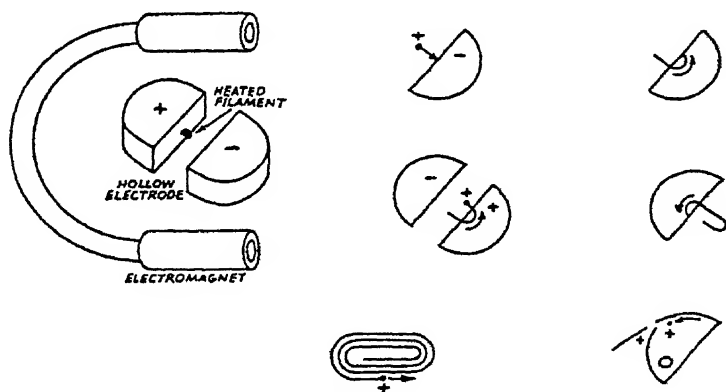


FIG. 16

often called 'the dees' because of their shape, are enclosed in a gas-tight container, from which all but a trace of gas has been removed. Between the two is a heated tungsten filament to ionize the gas: that is, to strike off an electron, and so leave the rest of the atom with a positive charge.

The vacuum chamber is fixed between the poles of a powerful electro-magnet; and in addition a powerful alternating electric field is applied to the conductors. One of these electrodes (one of the 'dees') may be at 40,000 volts positive, and the other at 40,000 volts negative.

When the gas in the container is deuterium the positive ions are deuterons. Let us follow one of these deuterons.

It is attracted, and accelerated, towards the negative electrode. As soon as it enters the electrode it is free from the electric field, and is no longer accelerated. But it is still subject to the magnetic field of the electro-magnet. This causes it to move along a circular path. When it has moved through half a circle it is once more in the space between the electrodes. The current alternations are synchronized with the movement of the deuteron. It reaches the gap just as the field is reversed, so it is accelerated toward the other electrode, which is now negative. In this it again swings round in a half circle. The angular velocity in these half circles is the same, whatever the radius. So the deuteron again reaches the open just as the field changes.

After circling many times, in a gradually widening spiral, at greater and greater speed, the deuteron reaches a point on the circumference where the electrode is cut away to allow it to escape. The cut is made half-way round, so that the deuteron reaches it just as the field is changing. For a moment the field is zero, and the deuteron escapes. It is deflected into a target chamber by a positively-charged plate.

We have followed the adventures of a single deuteron, moving at faster and faster speed round and round the cyclotron. It is not alone. Millions of other deuterons are being accelerated in the same way and delivered to the target chamber.

If a trace of ordinary hydrogen is used, the cyclotron delivers protons; with a trace of helium it delivers alpha-particles. The alpha-particles may be used to bombard beryllium in the target chamber, and this then ejects swift neutrons.

Atomic Explosions

The temperature in an atomic explosion goes up to millions of degrees; the pressure goes up to millions of tons per square inch. It is this enormous heat and pressure, together with the radioactivity of the products of the explosion, that distinguish an atomic explosion from an ordinary chemical explosion.

When the nucleus of an atom of U 235 is hit by a neutron it may undergo fission. There are several things to observe about the fissioning:

(i) The nucleus of U 235 contains a large number of neutrons: $235 - 92 = 143$. Not all of these 143 neutrons are retained by the atoms into which the U 235 atom is fissioned. So each fission releases more neutrons, each capable of causing further fissions. It seems as though the number of fissions should increase with great rapidity.

(ii) However, there are some checks on the increase. Neutrons may be absorbed without causing fission; that is how uranium atoms become atoms of neptunium. Some neutrons may be absorbed by impurities, and so lost to the possibility of further fissioning. Neutrons may be radiated into the air through the surface of the metal; these also would be lost.

(iii) Even if the average number of neutrons set free by fissioning is only a little greater than the number lost, the number of free neutrons, and therefore the number of fissions, does increase with great rapidity. These events are repeated many millions of times in a second, so the build-up is practically instantaneous.

(iv) Two methods by which neutrons escape without causing fission, can be controlled. By using pure materials the losses due to impurities may be almost entirely eliminated. A small piece of any substance has a large surface for its size; from a small piece of U 235 many neutrons escape through the surface, and there is no explosion. By bringing several pieces together we may reduce the combined surface so greatly that fissioning increases to the explosion point.

(v) The total mass of the fragments into which an atom of U 235 is fissioned is less than the mass of the original atom. Some of the mass ceases to exist as mass; it changes to energy. When millions of millions of millions of atoms are fissioned, all-but-

instantaneously, we get the vast temperature and pressure of an atomic explosion.

(vi) Plutonium is produced naturally by the reaction of neutrons on uranium atoms. But it occurs in nature only in barely detectable quantities. The possibility of nearly pure plutonium is remote in the extreme. When plutonium is manufactured, it has to be stored in small quantities, because larger quantities would give an atomic explosion. However, it may be rendered harmless by being mixed with boron, which absorbs neutrons.

The Hydrogen Bomb

At the lighter end of the table of elements the conditions are different. We have noted that the mass of a uranium atom is greater than the combined masses into which it is fissioned. Amongst the lighter elements the mass of an atom is less, not more, than the combined masses of the particles which compose it. The extra mass of the particles must be released as energy before the atom can be synthesized from its particles.

The helium atom, for example, has a mass of 4.0028 units, in the scale where the oxygen atom is 16. The atom consists of six particles: two protons, two neutrons, and two electrons. Their masses are:

$$2 \text{ protons: } 1.0076 \times 2 = 2.0152$$

$$2 \text{ neutrons: } 1.0089 \times 2 = 2.0178$$

$$2 \text{ electrons: } .00055 \times 2 = .0011$$

$$\text{Total mass : } \quad \quad \quad 4.0341$$

Thus the total mass of the particles is: 4.0341 — 4.0028 = 0.0313 unit more than the mass of the helium atom.

The conditions in which helium can be synthesized from its constituent particles are the all-but-infinite temperature and pressure of an atomic explosion. Such an explosion can be used to detonate a still greater explosion in which helium is synthesized. The explosion would consist of the change of surplus mass to energy, and the

sudden release of this energy. The extreme destructiveness of the hydrogen bomb is due to the large amount of material that can be detonated.

In Professor Gamow's account of the origin of the elements, he ascribes the synthesis of the elements from highly compressed neutrons to the same kind of conditions in an even more extreme form that exist in an atomic explosion.

Colourless Elements

The elements, that seem so dangerously built up out of exciting particles, are actually, in bulk, far from exciting to look at. There is not much colour amongst them. Sulphur has its bright yellow colour, and phosphorus its pale yellow or red. Fluorine is a pale yellow gas, and chlorine a deeper greenish-yellow. Gold has its burnished yellow, silver its brilliant white, and copper its elusive red. Sulphur and bromine are both bright red as gases. Zinc has a bluish colour. Iodine is lustrous black and carbon dull black, unless it is the transparent diamond. Zirconium and rhenium may be black powder, silicon a dark brown powder, and selenium a brick-red powder.

Out of the 101 elements we have listed fifteen that have some pretensions to colourfulness. For most of the rest we have to be content with off-whites and greys, except in the case of a few metals which are tinged with brighter colours: gallium and indium with blue, manganese with red, and neodymium with yellow.

Ten of the elements are gases at room temperature. These are hydrogen, nitrogen, oxygen, fluorine, chlorine, and the five inert gases: helium, neon, argon, krypton, and xenon. Only two of the elements are liquids at room temperatures: bromine and mercury. Six are solid non-metals: boron, carbon, silicon, phosphorus, sulphur, and iodine. Arsenic, tellurium, and selenium are dubious metals; they may be had in metallic form, conducting electricity, or as non-conducting powders. The remaining seventy or so elements are solid metals. All the elements from polonium (element 84) upwards have no non-radioactive forms.

Wide Range of Properties

The apparently unspectacular elements do, in fact, embrace a wide range of properties. We have a range of chemical reaction, from the great activity of oxygen, and the still greater activity of fluorine, down to the indifference of the inert gases. We have a range of density, from osmium that is $22\frac{1}{2}$ times as heavy as water, to hydrogen that has less than a ten-thousandth part of the weight of water. We have the diamond so hard that it is in a class by itself, and sodium and potassium so soft that they can be cut with a knife. We have gold and silver and copper that can be beaten out into thin sheets, or drawn out into thin wires, and we have sulphur so brittle that hammering powders it. We have magnesium that is harmless, arsenic that is poisonous, and lead that we have to be careful about. We have the special properties of carbon that enable it to form skeletons for the elaborate organic compounds. We have the exciting property of magnetism that iron shares, to a lesser extent, with cobalt and nickel. We have helium that remains obstinately gaseous till its temperature is nearly down to absolute zero, and carbon and tungsten and rhenium that are almost as obstinately solid. We have the common metals, lead, tin, zinc, copper, antimony, so strangely alike, so different in their uses. We have the hardness and tenacity of iron; and chromium and tungsten and molybdenum that harden and toughen iron.

With such a range of properties in the elements, it may well seem amazing that they should all be built up out of such an economy of ultimate materials :

protons with positive charges,
electrons with negative charges,
neutrons without charges,

and all of these so small that millions of them, and millions of millions, are insignificant. So that we have to have many millions of millions of millions before we reach a sizeable quantity.

The Table of Elements

It was Mendeleyeff who, in 1877, first published a table of all the known elements arranged on a rational basis. He put all the known elements in order of their atomic weights. He divided the elements into periods, and he showed that properties ran in sequences across the periods, and, more strikingly, in sequences down the periods. He also showed where there were gaps in the table; and he predicted, from their places in the periods, the properties of elements which would fill the gaps. His prophecies were verified when these elements were discovered.

There were some discrepancies in the table, but not many. In a few places the order of neighbouring elements had to be interchanged to make them agree with the chemical properties. Moseley's discovery of atomic numbers made the order of the elements quite definite. The discovery that the atomic weight is the average mass of the isotopes of an element, explained why atomic weights do not always agree with the chemical properties. However, Mendeleyeff's table remains substantially as it was when he published it.

In a modern form the table of elements includes:

- (i) Hydrogen and helium.
- (ii) First short period of 8 elements: lithium, beryllium, boron, carbon, nitrogen, oxygen, fluorine, neon.
- (iii) Second short period of 8 elements: sodium, magnesium, aluminium, silicon, phosphorus, sulphur, chlorine, argon.
- (iv) First long period of 18 elements: potassium, calcium, scandium, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, gallium, germanium, arsenic, selenium, bromine, krypton.
- (v) Second long period of 18 elements: rubidium, strontium, yttrium, zirconium, niobium, molybdenum, technetium, ruthenium, rhodium, palladium, silver, cadmium, indium, tin, antimony, tellurium, iodine, xenon.

VI

NEW CHEMICAL IDEAS

1. What is adsorption?
2. What is a catalyst?
3. Why is a large surface often desirable in a catalyst?
4. What is meant by 'poisoning' a catalyst?
5. How is sulphuric acid made by the 'contact' process?
6. How is ammonia made from atmospheric nitrogen?
7. What is a 'carrier'?
8. How can radium be isolated?
9. How does the Geiger counter operate?
10. How is artificial radioactivity produced?
11. What is tracer chemistry?
12. What is chromatography?
13. How has the process of photosynthesis been investigated?
14. What is a detergent chemically?
15. What is ion-exchange?
16. How can ion-exchange be used to produce very pure water?
17. How can it be used to separate metals?
18. How does fresh water enter the bodies of sea-animals?

TODAY we have to hand all the older methods ever available to ancient alchemists and modern chemists. In addition to these we have new methods that are evolved from time to time. Some of these methods enable the most minute traces of substances to be detected. Some of them enable reactions to be speeded up, or directed with great certainty.

Adsorption

Adsorption is the word we use for the formation of a thin film of one or more substances over the surface of another substance. The adsorbed film may be thin in the extreme; it may be no more than a single molecule thick across the whole surface.

The formation of the surface film is accounted for in this way. The molecules of a sheet of glass, for example, are attached to one another by their mutual attractions. At the surface of the glass the molecules are attached to other molecules below and at the sides; but there is no attachment above. The outward sides of the molecules are free to attach themselves to molecules of other substances, and so to form a surface film.

We breathe on a window-pane, and the pane is quickly covered with a film of moisture. But when we rub a finger on the pane, and then breathe on it, moisture does not form on the part that has been rubbed. Probably the finger leaves a thin film of grease, and moisture cannot form on the greasy surface. The film of grease need not be thick; but it is just thick enough to cover the glass surface which adsorbs moisture.

The adsorbed surface film does not go deep. When the reaction extends below the surface it is an ordinary chemical reaction. Hydrogen, for example, is adsorbed by nickel; it forms on the surface of nickel a film which is one molecule thick: that is, about one hundred-millionth of an inch thick. Carbon monoxide, on the other hand, reacts strongly with nickel. The reaction is much greater than the formation of a surface film by adsorption; the whole mass of nickel is converted into

greater is their combined area. When a lump of material has been reduced to the finest possible particles, the original area may be multiplied by as much as a million.

We also want the catalyst to be in such a form that the reacting molecules can readily get at it. It is a common practice to have the catalyst suspended in a porous framework. Asbestos is rigid enough for the purpose, it is very porous, and it does not readily take part in reactions; so it makes a good framework. When platinum is used as a catalyst, it is sometimes deposited on asbestos: this is platinized asbestos. The asbestos is soaked in platinum chloride, and then heated. The chlorine is driven off, and free platinum is suspended in the asbestos in a very fine state. Other porous substances are also used for suspending platinum.

Poisoning a Catalyst

Impurities in the materials we use for reactions may have serious effects on a catalyst. It may happen that one of the impurities forms a stable compound with the surface of the catalyst and so puts it out of action altogether. It would not require a great amount of an impurity to poison a catalyst in this way. There need not be much more than is required to form a layer one molecule thick over the surface of the catalyst.

When sulphuric acid is manufactured by the 'contact' process, sulphur dioxide is oxidized to sulphur trioxide, which gives the acid when it is dissolved in water. Platinum is used as a catalyst. In preparing the catalyst, platinum chloride is strongly heated with hydrated magnesium sulphate. The sulphate gives up water, and forms a porous mass of anhydrous magnesium sulphate. The platinum chloride decomposes, and free platinum is deposited in the pores of the sulphate in a very fine state. This form of catalyst works better than platinized asbestos.

The sulphur dioxide used in this process may be obtained by burning iron pyrites, which is sulphide of iron, or by burning sulphur. If iron pyrites is used there

is likely to be a compound of arsenic present as an impurity. This would poison the catalyst. It is better therefore to obtain the sulphur dioxide by burning sulphur, which is not likely to contain arsenic. When iron pyrites is used as a source of sulphur dioxide, the gas has to be freed from arsenic before it is oxidized to sulphur trioxide.

Nitrogen from the Air

All plants need nitrogen; they cannot grow without it. There is practically unlimited nitrogen in the air, but very few plants can draw on this vast store. However, plants of the pea family seem able to use atmospheric nitrogen. There are nodules on the roots of these plants in which live bacteria, known as *nitrogen-fixers*; these bacteria take nitrogen from the air, form it into compounds and hand it on to the plant in a form in which it can be used. When the plant dies the combined nitrogen remains in the soil. Lichens also use atmospheric nitrogen.

But most plants need nitrogen already combined with other elements. For that reason the manufacture of ammonia from hydrogen and atmospheric nitrogen is a very important process. The manufacture is carried out at high temperature and under great pressure. The catalysts used are trade secrets, but most of them are known to include ferric oxide. This catalyst is poisoned by carbon monoxide which is a common impurity of the hydrogen. The hydrogen must therefore be carefully freed from carbon monoxide before it is used.

Pore Adsorption

Porous substances, like charcoal, have a kind of adsorption called pore adsorption. There is a lot of surface available in the pores of charcoal, and this alone makes it a good adsorber. There is something else that makes it even more efficient. Some of the molecules seem to be trapped in the pores, so that they cannot move about as freely as when they are in gaseous form. They are closer together, and so take up much less room, and are in a sort

of liquid state. For these two reasons charcoal can take up a large amount of gas. This is especially observable when the charcoal has been previously freed from gas by heating it.

An interesting example of the use of charcoal lies in the production of very high vacua. To begin with most of the gas is removed by pumping. The charcoal used for adsorption is contained in a 'trap', and the trap is immersed in liquid air. The coldness increases the power of adsorption, and the charcoal takes up the last traces of air.

Charcoal is also used to take up matter that is to be got rid of because of its smell or colour. It is used, for example, to extract colouring matter from sugar solution, before the sugar is crystallized. The charcoal used for this purpose is animal charcoal. It is prepared from bones by boiling them to free them from fat, breaking them up small, and baking them in iron retorts. The animal charcoal contains only about 15 per cent of actual charcoal, but it is hard and full of pores. It is therefore very efficient for pore adsorption.

Charcoal is also used similarly to recover dyestuffs from water. The water is shaken up with the charcoal, and the dye is adsorbed. The dye may afterwards be washed out of the charcoal with alcohol. Charcoal is also used in gas-masks to adsorb noxious gases and fumes.

Carriers

Sometimes a substance has to be separated out from a superabundance of other material. The proverbial parallel is searching for a needle in a haystack. But even that apparently impossible task is not really impossible. If the game were worth the candle, it would be possible to recover the needle by attracting it to a powerful electromagnet.

To isolate radium from the minerals in which it is found seems almost as forlorn a hope as searching for a needle in a haystack, for 80 tons of pitch-blende contains a mere ounce of radium, spread evenly throughout the

mass. So small a quantity might easily be lost in the process of abstraction. However, radium does reveal its presence by its radioactivity, so that what happens to it can readily be traced.

To avoid accidental loss of the precious radium, a *carrier* can be used. The carrier is a substance chemically similar to the one that is being sought, which is usually a trace of radioactive metal. The same chemical reaction brings down both substances together, radium and carrier; their similarity keeps them together. Afterwards, if we wish to isolate the radium from its carrier, we have to find a chemical difference between the two.

Radium belongs to the group of elements known as alkaline earths. These elements are beryllium, magnesium, calcium, strontium, barium, and radium. Barium is the nearest element to radium in the group, and is therefore most like it in chemical properties. For this reason barium can be used as a carrier for radium. A salt of this metal is added to the pitch-blende from which radium is to be extracted. Radioactivity shows that radium and barium come down together.

The amount of carrier used has to be carefully considered. On the one hand, it must not be an impossibly small fraction of the whole bulk of matter being dealt with. On the other hand, it should not be so great as to swamp the small amount of matter being carried.

In seeking for a carrier for an unidentified element there are not usually many possibilities to be tried out. If one substance proves to be useless as a carrier, we try another. The problem is easier when we know the element, and therefore its chemical affinities.

The Geiger Counter

An electron is an extremely small thing. The hydrogen molecule has a diameter of about one hundred-millionth of an inch, and an electron is a very small fraction of that. It is truly amazing, therefore, that we should be able to detect a single electron, and even to count electrons.

The instrument commonly used for this purpose is the

Geiger counter. It is an essentially simple instrument. The vital part of the counter is a metal tube, with

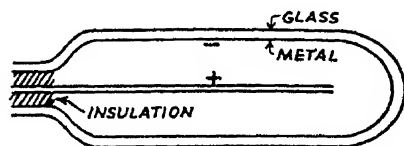


FIG. 18

a metal wire running down the middle of it, and insulated from it. Sometimes the tube is the metallized inner surface of a glass container; but, whatever form it takes, the tube must form a sealed con-

tainer. It may contain argon and alcohol at low pressure.

A high voltage is applied to the metal tube and wire. The tube is the cathode (negative electrode), and the wire is the anode (positive electrode).

When the counter is being used it is exposed to the radiation which is being investigated. A single electron enters the counter. It has practically no effect in itself, but it acts like a spark to a train of gunpowder. It is moving at high speed; it collides with gas molecules, and ionizes them. That is, it strikes off an electron at each collision, and so produces an ion pair: the negative electron, and the molecule which acquires a positive charge by losing the negative electron. Each one of the electrons thus struck off is moving at high speed; it collides with the other molecules and ionizes them. And so we have an extremely rapid increase in the number of ion pairs.

The negative ions (the electrons) are attracted toward the anode; the positive ions are attracted toward the cathode. The glass cylinder discharges, and a small electric impulse leaves it. This impulse is amplified, and used to operate a mechanical counter. As there is one impulse for each electron that enters, the instrument records the total number of electrons. In the newest counters, the counting is done electrically.

The process of ionizing the gases in the glass cylinder, and of ensuring the discharge, may seem complicated and slow. Actually it takes an extremely small fraction of a second. The cylinder recovers almost instantaneously, and is then ready for the next electron.

The counter can be used for other particles as well as electrons, provided they have the power of ionizing the gases in the cylinder by striking off electrons from the molecules.

Artificial Radioactivity

It is possible to give materials artificial radioactivity. The Joliot-Curies found this out in 1934. When they were bombarding boron nitride with high-speed particles, for example, they found that the nitride went on emitting electrons for an hour or two after the bombardment had ceased. The nitride had become temporarily radioactive.

This gives us the method of *activating* elements, as we say. That is, of making them temporarily radioactive. The method is to bombard the material with high-speed particles or, more usually, with slow neutrons. But other particles also are used, including alpha-particles, which have positive charges. Even hydrogen, the element farthest removed from the natural radio-elements, has been activated.

The advantage of using activated materials is that the Geiger counter enables us to detect the most minute traces of such materials. It can detect quantities so small that they are far beyond the reach of ordinary chemical methods.

Detecting by Radioactivity

When copper foil is bombarded with alpha-particles it becomes radioactive. It was suspected that the nuclei of the copper atoms had absorbed the alpha-particles. If so, the nuclei would have acquired two extra positive charges, and so the element would have risen two places in the table of elements. Atoms of copper would have become atoms of gallium, which is two places above copper. There was also a possibility that the atoms had acquired only one extra positive charge and so become atoms of zinc, which is one place above copper.

It remained to decide to which of the two elements copper had been transmuted. There was the difficulty

that the quantity of copper actually activated was extremely minute.

However, copper chloride and zinc chloride can both be separated from gallium chloride by shaking them up with ether. The gallium chloride dissolves in ether, but not the other two chlorides. Ether is a light liquid: it floats on water. So there would be a complete separation—gallium in the ether above, copper and zinc in the water below. On this we base the method.

We begin by preparing the chlorides. The activated copper target is put into hydrochloric acid along with some inactive gallium, that is gallium which has not been activated. The acid dissolves the unchanged copper of the target and the gallium, as well as the activated material; and so it forms the chlorides of these metals.

The solution of chlorides is shaken up with ether, and then ether and acid are separated. A Geiger counter shows that radioactivity is confined almost entirely to the ether; there is little or none in the acid. It is clear therefore that the radioactivity is due to an isotope of gallium, and not to an isotope of zinc. Copper has been transmuted to gallium.

The inactive gallium used in the experiment acts as a carrier for the activated gallium. Without it the comparatively few atoms of activated material might be lost through chance absorption.

The Bombardment of Boron Nitride

In an experiment in which artificial radioactivity was detected, the Joliot-Curies had bombarded boron nitride with alpha-particles. In a later experiment they had to decide which element had become radioactive: boron or nitrogen. If it were boron, then the capture of an alpha-particle by the nucleus would give the nucleus two extra positive charges, and so raise the atom two places in the table of elements. An atom of boron would have become an atom of nitrogen. It seemed likely that this was what had happened.

There was no need to add nitrogen as a carrier for the activated material, because nitrogen was already there in

the boron nitride. The experimenters added caustic soda to the boron nitride to bring off the nitrogen as ammonia. They found that the ammonia which came off carried the radioactivity with it. The new radio-element must be an isotope of nitrogen, originating in the capture of alpha-particles by boron nuclei.

Tracer Chemistry

Tracer chemistry is one of the most fascinating of the new methods available to research chemists.

The Geiger counter, as we have observed, can detect the most minute quantity of radioactive material. Such material can thus be used as a *tracer*, to show the presence of a certain element. When it is used in this way, a sample of the material to be tested is activated by bombardment. Thereafter, what happens to the bulk of the material can be traced by means of the few radioactive atoms that go with it. This is the method used in tracer chemistry.

Here is an example of the use of a radioactive indicator in solving a physiological problem. The problem was to find out how long it takes common salt to circulate through the body. Without the method supplied by tracer chemistry the problem seemed to be almost insoluble. But tracer chemistry was used and the matter simplified. A little common salt was activated by bombardment. The activated salt was dissolved in water, and drunk. It was quite harmless; the minute trace of radioactivity could do no harm. The whole of the body except one hand was screened off by means of a lead screen; the subject had only to put a hand through a hole in the screen. A Geiger counter was held near the hand, and in about three minutes it began to count. In that short time, the salt taken into the stomach had been absorbed into the bloodstream, and carried to the hand.

Phosphorus in a Sunflower

Another example of the use of tracer chemistry occurred in an experiment by Hevesy. He was studying the circulation of phosphorus in sunflowers. In particular he wanted

an answer to the question : did newly absorbed phosphorus go to all the leaves of a plant, or did it go only to new growth?

He allowed a sunflower to grow normally for some time. He activated a small quantity of a salt of phosphorus, and he made a weak solution of the activated salt. Then he placed the growing plant with its roots in the solution.

After a suitable time he examined the plant, leaf by leaf, with a Geiger counter. He found activated phosphorus in all the leaves. This indicated that phosphorus had circulated through the whole plant, that is through leaves that had formed before the roots had been placed in the solution, as well as through those that had been formed afterwards.

Millions of people have drunk 'tonics' containing salts of iron, in the hope of supplying a deficiency of iron in the body. We were variously told that the iron really is absorbed, and that it is not absorbed at all. The opinions were expressed with equal authority, though neither of them seemed to be based on good experimental evidence. The use of activated tonics enabled a proper investigation to be made. It appears that iron actually is absorbed only when there is a deficiency in the body.

A Cheap Substitute for Radium

We think of a cheap substitute as something less than good. But the substitute may be just as good as the original, or even better, with the cheapness an added advantage.

Radium is a rare and extremely costly metal. Activated sodium is sometimes used as a cheap substitute for radium in the treatment of cancer. It has some advantages over radium, in addition to comparative cheapness. It is easy to administer. It can be injected as an activated solution of common salt; or the patient may simply drink the solution, and in three minutes he has it at his finger-ends. In some cases the activated sodium might be even more effective than radium.

The activated form of sodium is prepared by bombard-

ing one of its salts with deuterons, which are the nuclei of heavy hydrogen (deuterium). Normal sodium is Na^{23} ; the activated form is Na^{24} . This is an unstable isotope of sodium. It emits electrons, and so decays to Mg^{24} , which is an isotope of magnesium. The atoms of Mg^{24} are in an excited state. That is, they have surplus energy which has to be disposed of; they get rid of this surplus by emitting gamma-rays. Having emitted their surplus energy, the Mg^{24} atoms settle down as ordinary, inactive, atoms of magnesium.

Activated sodium has two important advantages. The radioactivity is short-lived, and fades away almost completely in a week. And in the second place, the radioactivity ends in the production of traces of an entirely harmless metal, magnesium. Much was hoped from the use of activated sodium in cases where cancer had attacked the white corpuscles of the blood, especially as it would be largely confined to the bloodstream. There has been some success, but much less than had been hoped. However, the new methods of artificial radioactivity and tracer chemistry seem to open up fertile fields for useful research.

Chemical Blots

We mix a small quantity of red ink and black ink, and dilute the mixture with a little water. We drop a little of the mixture on a piece of white blotting-paper, and leave it to spread out.

An example I have before me has made a blot 3 inches across. The interesting thing about the blot is that it shows a chemical separation of the materials in the ink. There is an outer rim of very light grey, then a sharp edge forming a circle of bright red; inside this is a less clearly defined circle with a bluish tinge, then a circle with a purplish tinge; and in the centre a very dark circle.

Many generations must have noticed the variations in the appearance of blots. It was not till a few years ago that anyone seems to have realized that blots could be used for chemical analysis.

The method is now called *paper chromatography*, that

is, writing in colour on paper. A strip of white blotting-paper is hung over a glass rod. It is arranged so that a shorter end may dip into a

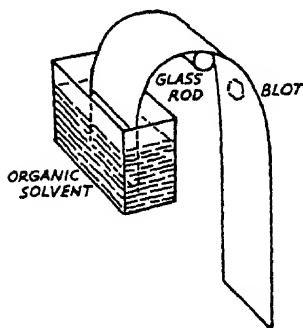


FIG. 19

shorter end may dip into a solution, whilst the longer end hangs down at the other side. A drop of a solution of the material to be analysed is dropped at the top of the paper on the longer side. The shorter side is then placed in a suitable organic solvent. The solvent siphons over, dissolves the material of the blot, and carries it down the paper.

Each substance in the material being analysed has its own degree of adsorption by the blotting-paper. Those most strongly adsorbed are held first; the others flow on, to be adsorbed lower down. So we have the various substances spread out, the more strongly adsorbed near the top, the others farther and farther down.

The next stage is to let a weak solution of a particular reagent run through the spread-out blot. The reagent produces the tell-tale colours that show which substances are present in the solution. This is an easy way of analysing minute quantities of various substances.

There are several variants of the method. One of these is to use two organic solvents. A blot is spread out, with one solvent, along the edge of the paper. The paper is then turned so that this edge is at the top. A second solvent is then used to soak up into the paper and carry the various substances at right angles to the original direction. The two solvents have different effects on the strength of adsorption of the various substances, so that the distances at right angles are different from those in the first direction. Each substance has, as it were, its x and y co-ordinates: so far in one direction, so far at right angles.

Another variant which is often combined with the previous one, is to use activated material in the analysis. That is to say, the material to be analysed is bombarded, and so rendered temporarily radioactive. The blot is

spread out, using two solvents, and dried. It is placed in contact with a photographic film, and thus a permanent record is obtained of the analysis. This record is compared with records of known substances obtained in identical conditions.

Investigating Photosynthesis

The manufacture of starch by plants, from carbon dioxide and water, is not a simple process. It proceeds by stages, and part of the process continues, at least for a short time, in the dark.

The problem of finding just what does happen is not an easy one. We are studying a process which proceeds for seconds, or at most for minutes, and which produces a complex mixture of products. And the quantities are so minute that ordinary chemical analysis is inadequate. It is indeed a case where the method of chromatography seems urgently called for. We use the radioactive method, because it is more reliable for very small quantities. We use carbon dioxide in which the carbon has been activated by bombardment; it is fed to the plants with which we are experimenting.

In one such experiment the plants used were chlorella, which is one of the green algae. The reactions in the plants were started by switching on a light. A few seconds, or sometimes a few minutes, later they were stopped by dropping the plants into alcohol. Everything was timed to a second.

Radioactive carbon, freshly incorporated in the plants, had now to be traced to the various compounds it formed. The dissolved materials were strung out by the method of chromatography. A photographic film showed the spots where the radioactive carbon came to rest. The photograph was compared with similar photographs of carbon compounds which might be present.

To find the comparative amounts of the various products, we go back to the original blot. The photograph showed where each product was situated on the blotting-paper. These spots were cut out, and examined with a Geiger counter.

The chromatograms were first of all compared with those of sugars, which have six carbon atoms in the molecule; they did not match. The radioactive spots were then cut out, and examined chemically. This suggested that one of the spots might be composed of a substance with seven carbon atoms in its molecule. It was chromatographed with this substance, and the two chromatograms proved to be identical. The material in a second spot was identified as a substance which has five carbon atoms in its molecule.

It has been suggested that the seven-carbon molecule splits into four and three. The four-carbon molecule afterwards splits into the two-carbon molecules needed for the six-carbon molecules of starch, whilst the three-carbon molecule provides the mechanism for the splitting.

Chromatography has certainly done much, and it seems likely that it can do more, to clarify the intricate process of synthesizing starch.

It has been found that photosynthesis continues if the green leaves are illuminated for the hundredth part of a second every ten seconds. One result of this discovery is that there is a considerable saving in the cost of the experiment. The chief cost is the lighting. It is now only necessary to illuminate part of the apparatus. The algae are kept circulating, so that they reach the illuminated part at suitable intervals.

Detergents

The post-war detergents have come on us from all sides, claiming this and that virtue. All alike have the advantage of not being fussy about the hardness of water. They ignore hardness; that is to say, they do not react with the dissolved matter, which makes the hardness, to form an insoluble scum.

A detergent is a fine chemical product, composed of carefully thought-out molecules. Each molecule has a hydrophilic head, and a hydrocarbon tail. That sounds as if it ought to be an antithesis, like black and white, or right and wrong; but it is not that at all. Hydrophilic means water-loving; the heads are attracted by water.

But hydrocarbon describes, not the proclivities of the tails, but their composition; the tails are compounds of hydrogen and carbon. The tails are sometimes said to be repulsed by water; but that is not so, they are strictly neutral. They only seem to be repulsed because the molecules of water attract one another, and so push the tails out of the way.

In a solution, the molecules of a detergent get together in small groups called *micelles* (my-cells). Each micelle has the hydrophilic heads pointing outward, and the tails tucked away in the middle. And so the micelle presents an unbroken hydrophilic front to the attracting water.

There is, or was, an attractive theory about the working of a detergent. According to this theory each micelle formed itself about a piece of dirt, and in this way particles of dirt were removed from places where they were not wanted. When we rinse the washed material, again according to this theory, the micelles carry the dirt down the drain.

There is, however, an objection to the theory. It seems that there are not enough micelles to do all that detergents do.

According to the newest theory, the micelles are like an invading army. They attack and displace the particles of dirt. So it seems quite reasonable to say that the dirt 'falls out'. That is the advertisers' statement of a respectable chemical theory.

There is plenty of material for the manufacture of detergents. Petroleum is a mixture of hydrocarbons, so it provides material for the hydrocarbon tails. Fats also supply carbon chains which can be used for the tails. And there is a large choice of substances which may be used for the hydrophilic heads.

Ion-exchange

We remind ourselves that ions are charged particles. The cations have positive charges. The hydrogen ion is H^+ , the sodium ion is Na^+ , the calcium ion is Ca^{++} (with a double positive charge), the magnesium ion is

Mg^{++} , and so on with other metallic ions. The anions have negative charges. The hydroxyl ion is OH^- , the chloride ion is Cl^- , and we have the acid radicals: SO_4^- , NO_3^- , and so on again.

It was discovered a hundred years ago that when a solution is poured on soil there may be an exchange of ions between the solution and the soil. Calcium bicarbonate, for example, may give up calcium to the soil, and receive sodium in exchange.

This exchange explains why lime keeps soil in a healthy condition. Soil which contains too much sodium is apt to be infertile. Soil containing magnesium or calcium tends to be more fertile. Calcium renders it granular, and therefore well aerated. When sodium-saturated soil is treated with lime there is an exchange of cations—sodium and calcium. The water in the soil washes out the sodium salt, and the soil gains calcium, which increases its fertility.

Softening by Ion-exchange

Magnesium and calcium are desirable in soil. They are highly undesirable in water used for washing and in industrial processes. The hardness of water is due to salts of these two metals. With soap they cause an insoluble scum, and so waste part of the soap. On the sides of boilers they form scale, which is a bad conductor of heat; greater heat is required for the boiler, and there is a waste of fuel. If we could arrange an exchange between magnesium and calcium ions on the one hand, and sodium ions on the other hand, we should have water free from the hardening materials. Sodium does not form an insoluble compound with soap, so the waste of soap ceases. And the sodium salts are soluble, and so do not form scale.

There is a natural deposit called greensand. It consists of grains of a green silicate, with some clay and sand; and it contains sodium. A thick layer of this material is sometimes spread over the sand in filter beds. When hard water passes through the greensand there is an exchange of ions. Calcium and magnesium ions go to the greensand,

and sodium ions go to the anions in the water. In this way the water is rendered soft.

When the greensand has lost all its sodium it is no longer effective. It has to be regenerated. This is done by passing through it a strong solution of common salt, which is sodium chloride. In this high concentration of sodium ions, the process of ion-exchange operates in the reverse direction. Magnesium and calcium in the greensand exchange with sodium in the solution. Thus the greensand gains sodium, and is ready for further water-softening.

The softening may not be completed in a single operation. But if the process is repeated still softer water is obtained. Repeated softening is carried out to get the really soft water which is used in boilers, and which prevents the forming of scale.

Ion-exchange Resins

The natural resins are usually exuded from plants; they are solid or semi-solid, with varied compositions; they may sometimes be found on the trunks of trees. These are the natural, organic, resins. They have been imitated, and there are many synthetic resins with properties similar to those of the natural resins. Amongst the synthetic resins, however, are some which have the valuable property of being ion-exchangers.

The synthetic ion-exchange resins have great advantages over such natural products as greensand. They can be made in any convenient shape, as grains, as rods, or as thin layers. They swell out in water, and in this condition the exchange of ions takes place very rapidly. There is a still more important difference. The natural materials appear to exchange only cations. But resins have been synthesized which exchange anions. Two synthetic resins may thus be used to obtain really pure water. We choose one resin which removes cations, and another resin which removes anions.

- (i) The cation-exchanger gives up hydrogen ions in exchange for metallic ions.

(ii) The anion-exchanger gives up hydroxyl ions (OH^-) in exchange for the chloride ion (Cl^-) and other anions.

(iii) The released hydrogen and hydroxyl combine to form water. Thus the combined effect of the two resins is to replace the dissolved matter with pure water.

Cost of Regeneration

The ion-exchange resins can be used over and over again, after regeneration. The two resins are usually kept apart, each in a separate tube. This means that they can be treated without having to be separated first. The cation-exchanger is washed with hydrochloric or sulphuric acid which removes the metallic ions. The anion-exchanger is washed with caustic soda to remove the anions. The two resins are then ready to be used again.

The expensive part of the process is the cost of acid and caustic soda used in regeneration. In fresh water the amount of dissolved matter is small, so not much of the expensive materials is required. Ion-exchange is indeed an economic way of obtaining quite pure water from water that is already fairly soft. It is much less costly than obtaining pure water by distillation.

Sea-water contains a very large amount of dissolved salts, and so to obtain fresh water from it frequent regeneration would be necessary, and the cost would be excessive. The method is not at present feasible as a means of obtaining fresh water from sea-water, though it has been used as an emergency measure, and there is the possibility that further discoveries may make it possible to extend the method to large-scale production of drinking-water from the sea.

Separating Metals

Ion-exchange can be used to separate two metals that are difficult to separate by other means. A tube is filled with a cation-exchange resin, because we want to separate metallic cations. A small amount of a solution of salts

of the two metals is poured in at the top. Ion-exchange takes place: the resin gives up hydrogen ions in exchange for metallic ions. The metals are adsorbed near the top of the column.

A little acid is allowed to drip in. The metals displace hydrogen in the acid, and dissolve again. The solution runs a little way down the tube. The rates at which the two metals run down depend on the strength of adsorption: the more strongly adsorbed metal lags behind the other. There is thus a partial separation of the two metals.

Repetitions of the process, in which acid is allowed to drip in slowly, increase the separation. Finally the two metals reach the bottom of the tube, one after the other. We have the word *elute* to describe what occurs, and that means to wash out. We say the two metals are eluted separately at the base of the tube.

The rare-earth metals are a group of fifteen metals: numbers 57 to 71 in the table of elements. The properties of these metals are so similar that it is extremely difficult to separate them. They have now been separated with comparative ease by the method of ion-exchange. The use of activated materials enables the metals to be detected as they are eluted, one by one, from the base of the tube.

Waste from industrial concerns often contains valuable materials in very weak solution. Recovery of such materials by evaporating the water would be disproportionately expensive. Ion-exchange provides a method of recovering them at an economic cost. The waste is passed through suitable cation-exchange resins. These resins exchange cheap ions, like hydrogen or chlorine ions, for the valuable ions in the waste. Thus the valuable material is concentrated in the resin, from which it can be recovered, and used.

Fresh Water in Sea-animals

At one time a difficult problem was posed by those animals which live exclusively in the sea and yet have fresh

water in their bodies. A herring is completely surrounded by salt water, but the water in its body is not salt; its flesh does not taste salty. A young whale is said to grow at the rate of a hundredweight a day, and the bulk of the increase is fresh water. Yet the whale also is completely surrounded by salt water.

Ion-exchange offers some sort of solution.

A living cell is surrounded by a membrane, and the degree of concentration of various materials inside the membrane is often quite different from that in surrounding fluid. The membrane of the cell wall appears to act as an ion-exchanger. Some membranes act as cation-exchangers, and only cations are transferred across them. Others act as anion-exchangers, and allow the passage of anions only. Membranes in the fish appear to act as anion-exchangers; they stop the passage of cations, and especially the sodium ions. And so we get the salt stopped by the membrane, and only pure water going through.

It should be clear, however, that there is as yet no adequate solution of the problem: why does water move in living material in a direction opposite to that in which it would move in non-living material? The movement of water we expect is towards the salt solution; the movement we get is from the salt solution into the fish's body.

VII

CHEMISTRY OF VOLCANOES

1. What are the temperatures of lava?
2. How are shield volcanoes formed?
3. How does volcanic pressure vary?
4. Which was the greatest explosion on record?
5. What is the probable origin of oceanic water?
6. Which are the chief reagents in volcanic eruptions?
7. Which are the chief products of volcanic activity?
8. How is sulphur produced by volcanoes?
9. Why is chemical reaction very active in eruptions?
10. Which chemical compounds are deposited by volcanoes?
11. What is the origin of volcanic gases?
12. How are the cavities formed in lava? What is found in them?
13. What is Iceland spar?
14. Which poison gases are erupted by volcanoes? Which are removed by rain?
15. Which metals have been found in volcanic deposits?
16. What are metamorphic rocks? How are they formed?
17. Which of man's methods are paralleled by volcanoes?
18. How has marble been made artificially?

A VOLCANO has at its disposal some of the most important chemical methods. It has these on a large scale, and sometimes in extreme forms. Where the experimental work of the chemist is directed to specific ends, volcanic chemistry is entirely haphazard; but in spite of this, the apparently undirected efforts of volcanoes do produce important results.

A volcano has a range of high temperatures. The temperature of the lava which is poured out is usually about $1,100^{\circ}\text{C}$. This is not much higher than the temperature needed to enable the lava to flow; it ceases to flow when the temperature has fallen to $1,050^{\circ}\text{C}$. As a rule, therefore, lava is viscous stuff which does not flow at great speed. Only at Kilauea, the famous volcano of Hawaii, does the temperature rise higher. Here it goes up to $1,200^{\circ}\text{C}$. and sometimes to $1,300^{\circ}\text{C}$. At this range of temperatures the lava is as fluid as water. It is sometimes thrown up in fountains to a height of hundreds of feet. And it rushes out in floods to a considerable distance, and so produces the low, flat cones that are called *shield volcanoes*, because they have some resemblance to shields. There are old shield volcanic cones in Iceland, but the production of new ones seems to have ceased.

Volcanoes are also subject to a range of extremely high pressures. The pressure is often sufficient to force the molten rock, which is lava, to a height of thousands of feet, so that it pours out from the summit of a high mountain. Sometimes the pressure is fairly steady, and continues for a long time. Sometimes it is violently explosive, and correspondingly short-lived. Probably the greatest explosion of modern times was that at Krakatau in the East Indies in 1883. In this explosion, or rather series of explosions, $4\frac{1}{4}$ cubic miles of rock was blown to rubble and dust.

Volcanic Water

The volcanic laboratory has a wide range of reagents available which come together and react as they do in chemical experiments.

Steam is present in abundance. It has been estimated that in some minor volcanic eruptions steam forms more than 99 per cent of all the materials ejected. That is exceptional, but there certainly is a large amount of steam coming from volcanoes. Much of the steam probably comes from rain that has percolated deep into the heated rocks below. But some of it appears to be what is called *juvenile* water: that is, water incorporated in rocks below the volcano, which appears on the earth's surface for the first time during the eruption.

'Ejected' is hardly the right word to use for what happens to the steam, because the steam does most of the ejecting. In the cold upper air, to which steam and ejected materials alike are thrown, the steam condenses and falls as deluges of hot rain.

The origin of the vast amount of water that fills the oceans has always been a problem. It seems to be highly improbable that the water could ever have formed an atmosphere about the earth. The most widely held opinion now is that the water of the oceans came from the crust of the earth. Volcanoes erupt vast quantities of juvenile water, and across millions of years this has been sufficient to fill the oceans.

Volcanic Reagents

Much research on volcanic activity has been done on the small subsidiary outlets called *fumaroles*. These are easier to approach and study than the uncomfortably big and dangerous volcanic cones. There is in Alaska a valley called the Valley of Ten Thousand Smokes. The many fumaroles in this valley are caused by an intrusive sheet of the rock called rhyolite, beneath the valley.

Three of the chief reagents from these fumaroles are hydrochloric acid, hydrofluoric acid, and sulphuretted hydrogen. The quantities are far from being negligible. In a single year the amounts were estimated at:

hydrochloric acid—over a million tons
hydrofluoric acid—200,000 tons
sulphuretted hydrogen—300,000 tons.

Such ejections, occurring over long periods, and from many volcanic centres, must add greatly to chemical activity on the earth's surface.

Next to water in quantity comes carbon dioxide. Volcanoes are adding huge quantities of this gas to the atmosphere. It is said that if the eruption of carbon dioxide were to cease, life would soon disappear from the earth.

Amongst other reagents ejected by volcanoes are: gaseous sulphur and sulphur dioxide; carbon monoxide; nitrogen and hydrogen; ammonia.

Volcanic Sulphur

One of the most interesting and important reactions connected with volcanoes is that between malodorous sulphur dioxide and the still more malodorous sulphuretted hydrogen. These two gases react when water is present, and there is plenty of water about a volcano in eruption. They react to form sulphur and water. The sulphur is deposited on any cool surfaces there happen to be. The small amount of water joins the superfluity of water already there.

Round a volcano in eruption quite a large quantity of sulphur is deposited. This comes partly from the gaseous sulphur which is erupted, and partly from the reaction between sulphur dioxide and sulphuretted hydrogen. Sulphur is one of the most useful products of volcanic action.

Sulphur has some truly romantic associations, though its title to fame is rather Mephistopholean. The unpleasant smell it makes when it is burning renders it appropriate as a fuel for the nether regions, and we commonly associate it with the Prince of Evil. Apart from its associations, however, it is much sought after, and there always seems to be a world shortage, in spite of the fact that volcanoes produce much new sulphur every year, and that there are large ancient beds of sulphur. Sulphur is used in the manufacture of sulphuric acid. This acid is so important to the chemical industries that the amount of sulphuric acid made

is often taken as an indication of the prosperity of a country's chemical industries.

Mount Punace, in Colombia, has a cap of sulphur which emanates from its own crater. Every year it adds to the cap an amount estimated at 15,000 tons. In Armenia the people are said to shoot their sulphur: Mount Alaghez pours out liquid sulphur high up in inaccessible spots, and the people use rifles to bring it down.

Beds of sulphur are sometimes found in the neighbourhood of volcanoes, especially where the beds are protected, by sediment, from oxidization. Those of Sicily are well known. Sulphur beds in an old volcanic region round the Dead Sea have a special interest. It has been suggested that Sodom and Gomorrah, the cities of the plain, were destroyed by a flash of lightning which fired sulphur and bitumen in the surrounding country. Bitumen is another inflammable volcanic product.

Other Volcanic Reactions

The atmosphere in a volcanic eruption is highly excited. The temperature is high enough to promote many reactions. Pressure is both great and variable. Water, which is necessary to many reactions, is there in abundance. Many metals are present in the erupted matter, and some of these probably act as catalysts for particular reactions. We have, indeed, though certainly in a haphazard way, the conditions that the chemical industries take great pains to produce. There are, therefore, many other reactions besides that between sulphur dioxide and sulphuretted hydrogen.

We have in particular the very conditions in which ammonia is made from atmospheric nitrogen: high temperature and pressure, a suitable catalyst (ferromagnesian minerals), and supplies of free nitrogen and hydrogen.

The presence of free hydrogen is not even necessary: the nitrogen can take the hydrogen from water.

Hydrochloric acid reacts with ammonia to produce

ammonium chloride. This settles on cool surfaces as a white incrustation. Chlorine unites with iron to make ferric chloride, which forms a yellow incrustation on cool surfaces.

Fumaroles in Tuscany produce ammonium borate.

Ferrous iron in the molten lava can take oxygen from water, and so be oxidized to the ferric state, as magnetite, which is often found in volcanic rocks.

One important reaction is ascribed to submarine eruptions. When sheets of lava erupt under the sea into rocks composed of calcium carbonate, carbon dioxide is driven out; the temperature of $1,100^{\circ}$ C. is quite high enough for this to occur. The carbon dioxide is replaced by silica, and the carbonate becomes a silicate. Hydrochloric acid also reacts with calcium carbonate; it releases carbon dioxide just as it does in a familiar school experiment.

Origin of Volcanic Gases

There seems to be little doubt about the origin of the gases that are so plentiful in volcanic eruptions. Igneous rocks have been heated to redness in a vacuum, that is, to about the temperature of lava. In these conditions they give off the volcanic gases. Meteorites also give off these gases when they are heated. It seems therefore that the gases were originally included in the rocks.

The faint flames of burning hydrogen have been seen over Kilauea. The hydrogen probably came from water. We have seen that in volcanic conditions ferrous iron can take oxygen from water and so free hydrogen.

It has been observed that the vapours from Kilauea contain little chlorine. This is surprising, for Kilauea is near the sea. So many volcanoes are near the sea that it had been assumed that much of the water they erupt came from that source. But sea salt consists very largely of sodium chloride. It therefore appears that the water vapour from this particular volcano does not come from the sea. It seems to come almost entirely from percolating rain, in addition to the juvenile water from igneous rocks.

Bubbles and Cavities

Molten rock, the lava of volcanoes, is seething with gases, chief amongst them the superabundance of super-heated steam. When the lava cools and solidifies, bubbles of the gases are trapped in it and form spaces in the rock. These spaces may be the very minute ones which occur in pumice, and which give pumice its peculiar and useful roughness. On the other hand, the spaces may be so large that they are better described as cavities than as bubbles.

Large cavities are sometimes found in old lavas, and these cavities have various minerals deposited in them. One of the commonest of these minerals is quartz, which is the basis of sand. Often there are large, well-formed crystals of quartz. These crystals are six-sided prisms ending in six-sided pyramids. Sometimes the quartz crystals have bands of coloured material across them; they are then called agates. Agates are sometimes also called Scotch pebbles, because they are found in parts of Scotland. They are polished, and used as ornaments.

Calcite is another mineral found deposited in lava cavities. It is a form of limestone, or calcium carbonate, which has been crystallized by heat. Iceland spar is a transparent form of calcite. It is famous for having double refraction, so that two images of an object are seen through it. The double refraction makes Iceland spar important for some optical instruments. The Nicol prisms of a geological microscope, for example, are made of Iceland spar. The whole world supply of the best quality Iceland spar comes from a single gas cavity in Iceland.

Other useful minerals found in gas cavities are the 'green earths'. These minerals are silicates of iron and magnesium. That is to say, they are compounds of silica (quartz is crystallized silica) and iron and magnesium. The green earths are used by artists as pigments.

Poison Gases

There is some carbon monoxide amongst the gases poured out by volcanoes, and carbon monoxide is indeed

an extremely poisonous gas. However, there is not much of it, and what little there is disperses harmlessly in the upper atmosphere.

This is not at all true of some of the other gases that pour out of volcanoes. The small amounts of poison gases produced by men are insignificant compared with the quantities sometimes emitted by volcanoes.

There was a disastrous eruption in 1902 of Mont Pelée and La Soufrière in the Lesser Antilles. During this eruption white-hot clouds of gas and solid particles were blown out at intervals. Instead of rising and dissipating in the upper air, as usually happens, these dreadful clouds billowed down the mountain-sides. One of the clouds swept over St Pierre, the capital of Martinique. In a moment the houses were thrown down and set on fire, and the whole population of 30,000 was wiped out.

Carbon dioxide is not usually a poison gas, as we have pointed out in another chapter. But when it is produced in enormous quantities it may form suffocating layers that are dangerous. Carbon dioxide is one of the chief products, second only to water, in the later stages of volcanic activity. It is produced in quantity just before the final stage, at which water alone is erupted.

Some gases that might be dangerous in quantity, are in fact harmless, because they are quickly removed from the atmosphere. Hydrochloric acid and hydrofluoric acid are brought down in solution by rain; they form chlorides and fluorides in the soil. Sulphur dioxide and sulphur trioxide are brought down as sulphurous and sulphuric acids. They form sulphates in the soil.

Volcanic Metals

Many metals have been found about volcanoes, round fumaroles, and in volcanic deposits. This is rather what one might expect, since a volcano erupts any sort of material that happens to be in the rocks below it. What may be unexpected is that the metals are not evenly dispersed throughout the deposits. Chemical activity and attraction brings each metal, more or less, into one spot,

or a few spots. The heated atmosphere, with its many reagents, acts as a means of sorting out the metals. Thus, in fumaroles of the Valley of Ten Thousand Smokes several tons of magnetite were plainly visible. Copper characterizes the fumaroles of Etna, and lead the fumaroles of Vesuvius.

The metals that have been found about volcanoes include lead, copper, tin, zinc, and oxide of iron. It will be seen that these include most of the common metals, again as one might expect. But the rarer metals also sometimes occur. There is, for example, gold in the sulphur of La Sufra in Colombia, and mercury, antimony, and arsenic, are among other metals that are sometimes found.

Heat and Pressure

The great heat of volcanoes has very striking effects on surrounding rocks, especially when the heat is accompanied by great pressure, as it usually is. The rocks are changed physically, and sometimes chemically. We get the many kinds of rock that are classed as metamorphic, because their forms have been changed.

Some of the changes are similar to changes regularly carried out by man. Beds of coal are sometimes baked into coke, just as coal is baked in gas-ovens. The coal would have to be protected by layers of rock above it; otherwise it would simply burn away. And clay is sometimes baked into a kind of rough porcelain.

One of the most interesting reactions is that with limestone. Very often it happens that molten rock is forced up into cracks in the rocks above. The molten rock may spread out between the layers of these rocks. It forces the layers apart, and thus forms an intrusive sheet between them. When this happens to a bed of limestone, the limestone is subjected to great heat and pressure. It is baked into the crystalline form of calcite. When the heat and pressure are still greater the calcite is baked into the much harder crystalline form of marble.

The making of marble from limestone is not a regular

manufacturing process, but it has been done experimentally. It may be remembered that when limestone is heated to a cherry-red heat it breaks up into quicklime and carbon dioxide. This only happens when the temperature is high, and when the carbon dioxide is free to escape. The experiment was based on these ideas. Powdered limestone was shut up in an iron box, and it was kept at a dull red heat for several days. After this treatment the limestone was found to have crystallized as marble.

We have noted that at the temperature of molten lava, ferrous iron can take oxygen from water, thus releasing hydrogen, and itself becoming ferric iron. The hydroxide of iron also is oxidized to haematite or magnetite. In the metamorphic region round Lake Superior haematite and magnetite are found in an almost pure state.

VIII

CHEMISTRY OF THE UNIVERSE

1. How do we obtain knowledge of the universe?
2. What great difficulty arises in studying the atmospheres of planets?
3. What is the probable date of formation of the universe?
4. How were the elements probably formed?
5. Which are the chief elements in the universe?
6. Why are some compounds found in comets which do not exist on the earth?
7. How was helium discovered?
8. What is the probable composition of the sun?
9. What is the Bethe cycle? What other series of reactions is possible?
10. What is the source of the sun's energy?
11. How do we inquire into the earth's interior? What is the probable arrangement of rocks there?
12. What was the probable origin of the earth's atmosphere?
13. Why is there so much argon in our atmosphere?
14. What is the origin of free oxygen in the air?
15. What sort of an atmosphere has Venus?
16. What is known of the atmosphere of Mars?
17. What possibility is there of life on the other planets?
18. What is the probable composition of Jupiter?
19. How do the atmospheres of the major planets differ from those of the minor planets?
20. Which heavenly bodies have been described as 'gigantic snowballs'?

SPECTRUM analysis and nuclear research have extended greatly our knowledge of the chemistry of the universe. There are many new techniques. We can examine photographically the infra-red spectrum and the ultra-violet spectrum, as well as the rainbow spectrum. But though instruments and methods have been greatly improved, the difficulties are still formidable.

Our knowledge of the atmosphere of Mars is, for example, derived from a study of sunlight which has been reflected to us from the planet. This light has passed twice through the atmosphere of Mars, once on its journey to the surface of Mars, and again on the return journey. We compare the spectrum of the reflected light with the solar spectrum, and we look for changes made by the double journey through the Martian atmosphere. These changes might tell us what composes that atmosphere.

But there is a great difficulty. The reflected light also travels through our own atmosphere before it reaches us. The effects of gases in the Martian atmosphere would be the same as those of the same gases in our own atmosphere. We can introduce a difference by photographing spectra when Mars is approaching us and when it is receding. In the first case there would be a shift of the Martian lines toward the blue and in the second case toward the red. But the shifts are slight, and difficult to interpret.

However, knowledge accumulates as a result of patient and persistent research work, and the careful consideration of results. Some facts are well established, others are reasonably sure, and some are doubtful.

In the Beginning

The origin of the universe is now fixed, with some confidence, as an event that occurred 5,000 million years ago. Professor Gamow called the event, rather apologetically, 'creation', and also 'the Big Squeeze'. Others call it a 'momentary catastrophic happening'.

To whatever cause we attribute the event, it seems to be agreed that 'in the beginning' means 5,000 million years ago.

Many scientists have speculated on the state of the universe in the beginning. We have to work back from the state of things as they are now, the physical and chemical state of today, to that vast original event. The quasi-certainty of the time is based on the fact that various ways of calculating it produce approximately the same figure.

We have the possibility that there was simply a vast mass of neutrons. Superlatives fail when we try to give an idea of size—all the matter of the far-flung universe compressed into a compact mass of neutrons.

The physical conditions for such a state would have to be almost as extraordinary as the event itself. The temperature would be somewhere between ten thousand million degrees and a hundred thousand million degrees. The pressure would be somewhere between that of ten million million atmospheres and that of a thousand million million million atmospheres. The density of the primordial mass of neutrons would be correspondingly great, at least ten million, and possibly as much as a million millions.

That is the sort of picture we are given of the beginning. The excitement of the neutrons would be excessive. In that excess of energy neutrons would eject electrons, and so become protons. There would be a mass of protons and neutrons of such vast energy that nuclear reactions were possible. In this excited atmosphere the heavier elements would have been synthesized out of neutrons and protons.

The synthesis took place in a universe that began at once to spring wildly apart, and so to lose its excessive pressure and temperature. Gamow came to the conclusion that a single hour is all the time that can be allowed for the synthesis of the heavier elements. After that short period, temperature and pressure would be too low for further synthesis.

A Universe of Gas

We are chiefly dependent for our knowledge of the chemistry of the universe on light, and to a lesser extent on heat. The methods of spectrum analysis give a good picture of the chemical composition of the universe, and the results of measuring heat add to the picture.

All evidence points to the fact that the chemical composition of the universe is the same everywhere. The proportions of the elements vary within very wide limits, but they are the same elements, responding in similar ways to various conditions of heat and pressure. Where unusual compounds exist they can be accounted for by unusual conditions. In comets, for example, the molecules OH, CH, and CN have been detected. These molecules are so reactive that they can only survive for fractions of a second in earthly conditions. They can exist in comets, because cometary gases are so tenuous that collisions between the molecules are rare events.

So many earthly elements have been found in the sun's atmosphere that the composition of the sun has been described as that of the Earth, plus vast amounts of hydrogen and helium.

The stars known as white dwarfs have densities vastly greater than anything on earth. But that is ascribed, not to a difference in the elements, but to the atoms being stripped of electrons, so that the dense nuclei lie very close together.

Helium got its name from the Greek *helios*, the sun. It received this name because it was discovered by means of lines in the solar spectrum that did not match those of any known element. But it turned out that helium is not an element confined to the sun's atmosphere. There is helium in our own atmosphere; there is helium in radioactive rocks; there is helium in gas from oil wells. Taken all together, however, there is very little helium in the Earth.

This is rather surprising, because helium is one of the major constituents of the universe. It has been estimated that over a third of the matter of the universe is helium,

and not far short of two-thirds of it is hydrogen. The remaining ninety or so elements make up not much more than $1\frac{1}{2}$ per cent of the universe.

It seems that we live in a gaseous universe, with a very small amount of solid matter, and a still smaller amount of liquid. The reason for the preponderance of the very light elements is that these elements make up the bulk of the stars, and also the interstellar gas, which is the extremely tenuous gas between the stars. The heavier elements are largely confined to planets and satellites.

The interstellar gas is so tenuous that a volume of it equal in size to the earth would weigh no more than a hundredth of an ounce. Nevertheless, the spaces between the stars are so vast that the interstellar gas makes up a mass greater than that of all the stars. Various metals have been detected in this gas: sodium, calcium, potassium, iron, titanium, and some of the unstable compounds found in comets; but far and away the most abundant element is hydrogen.

The Sun

An estimate of the composition of the sun is: hydrogen 55 per cent; helium 11 per cent; carbon, nitrogen, oxygen, fluorine, and neon 34 per cent. Metals make up no more than a quarter of one per cent.

The greater part of the sun is a mixture of hydrogen and helium. But these gases are not at the low density of, say, the earth's atmosphere. Because of the great size of the sun, the pressure at the centre is enormous, and so, therefore, is the density. The densest substance on earth is osmium, which has a density of $22\frac{1}{2}$; it is $22\frac{1}{2}$ times as heavy as water. The density of the centre of the sun has been calculated as 100, and that is nearly $4\frac{1}{2}$ times the density of the densest metal. The sun is a gas under enormous pressure. It is still gaseous, because the temperature is high above the critical temperature at which a gas can become liquid. The temperature at the centre of the sun is similar to that of most other stars: it has been calculated to be 20 million degrees.

The sun radiates enormous quantities of energy, the

source of which has long been a matter of speculation. It is now thought to arise from the change of mass into energy. It has been known for some time that energy may be released in nuclear reactions. This occurs in the synthesis of the lighter elements from their constituent particles.

A helium nucleus may be synthesized from four protons, by the ejection of two positrons: these have the same mass as electrons. The mass of a helium atom is 4.00389. So 4.00389 is the mass of a helium nucleus plus two positrons.

$$\text{Mass of 4 protons} = 1.00758 \times 4 = 4.03032$$

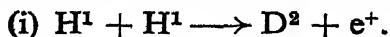
$$\text{Mass of He nucleus and 2 positrons} = 4.00389$$

Difference	0.02643
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So there is a loss of 0.02643 units of mass when a helium atom is synthesized from four protons. And there is a further small loss by the annihilation of the positrons.

The next problem is to find a series of reactions which would make such a synthesis possible. In the extremity of temperature and pressure at the centre of the sun, we have the conditions, the ignition point, for the nuclear reaction. The equations which describe the reaction are nuclear equations, not ordinary chemical equations. Thus H^1 stands for a proton, because a proton is a nucleus of ordinary hydrogen. D^2 stands for a deuterium nucleus, with mass 2. e^+ stands for a positron.

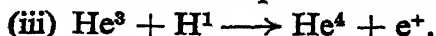
The series of reactions which meets the requirements is:



Two protons unite, and eject a positron. The ejection of a positron by a proton removes the positive charge, and thus changes the proton to a neutron. So we have the proton and neutron which form a deuterium nucleus (D^2).



The deuterium nucleus absorbs a proton, and thus becomes a nucleus of He^3 , with two protons and a neutron. He^3 is a short-lived isotope of helium.

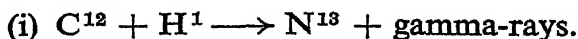


The He^3 nucleus absorbs a proton and then ejects a positron. This gives the He^4 nucleus with two protons and two neutrons. He^4 is the nucleus of ordinary helium.

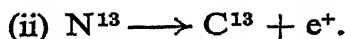
The net effect of the three reactions may be seen by cancelling everything that occurs on both sides of the equations. Four protons form a helium nucleus by ejecting two positrons.

These reactions may be the chief source of the energy radiated by stars, especially by the cooler stars.

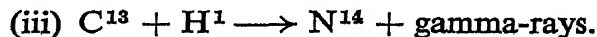
Another possible series of reactions is called the Bethe cycle, after its discoverer. For those who like to follow the cycle, here it is:



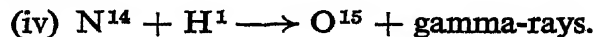
A C^{12} nucleus absorbs a proton. It thus becomes a nucleus of the next higher element, which is nitrogen. It becomes a nucleus of N^{13} which is a short-lived isotope of nitrogen. Surplus energy is radiated as gamma-rays.



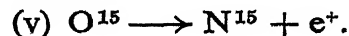
The N^{13} nucleus ejects a positron, and thus changes one of its protons to a neutron. The loss of a proton takes it back to a carbon nucleus. But the number of nuclear particles (protons and neutrons) is still 13, so the nucleus is C^{13} . This isotope forms nearly $\frac{3}{4}$ of one per cent of ordinary carbon.



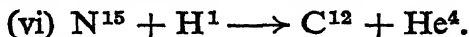
The C^{13} nucleus absorbs a proton, and so becomes an N^{14} nucleus. This isotope forms much the greater part of ordinary nitrogen. Surplus energy is radiated as gamma-rays.



The N^{14} nucleus absorbs a proton. It thus goes up one place and becomes a nucleus of O^{15} , which is a short-lived isotope of oxygen. Surplus energy is radiated as gamma-rays.



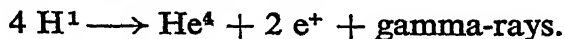
The O^{15} nucleus ejects a positron, and thus changes a proton to a neutron. The loss of a proton takes it down one place, to nitrogen. But the number of nuclear particles remains unchanged at 15. N^{15} is a rather uncommon isotope of nitrogen.



The N^{15} nucleus absorbs a proton. It then ejects a nucleus of He^4 (2 protons and 2 neutrons). There is a gain of one proton, and a loss of two protons and two neutrons. The net loss of one proton takes N^{15} down to carbon. The net loss of three nuclear particles takes the mass down from 15 to 12. So it becomes a nucleus of C^{12} .

The cycle ends here because we have returned to C^{12} , with which we started. C^{12} is thus a catalyst for the cycle of reactions, and it is ready to catalyse another cycle.

We cancel everything that occurs on both sides of the equations. We are left with:



The Bethe cycle requires a higher temperature than that for the first series of reactions. The net effect in both cases is to change four protons to a helium nucleus by the ejection of two positrons.

A point of great interest is that the sun and the stars are using up their reserves of hydrogen, some of them conservatively, and some wastefully. The hydrogen cannot be replaced. When it has all been changed to helium, the chief source of energy in a star is gone. After that the star slowly dies as it gradually cools down. It may do odd things before it finally expires. It may contract into a 'white dwarf', with a density so extravagant that it strains one's credulity to believe it. Or it may flare out as a 'nova'. But whatever it does, once the reserves of hydrogen are exhausted, it is on the path to extinction.

The Earth's Interior

Men have always made guesses at what there is in the interior of the Earth. One thing at least seemed certain

enough: the interior of the Earth is very hot. There seemed to be plenty of evidence for the theory of a very hot Earth with a cool crust. There was the steady increase in temperature as one descended into mines; there was the evidence of hot springs and hot volcanic material coming up from below; there was the crumpling of the Earth's crust as it adjusted itself to the cooling and shrinking interior.

We are no longer so certain about extreme heat in the centre of the Earth; there are other ways of interpreting the evidence, and none of the evidence relates to very great depths. But we have new ways of prying into the Earth's interior.

We have the evidence of density. The density of the Earth as a whole is $5\frac{1}{2}$. The density of the surface rocks is between 2 and 3. Evidently there must be heavier rocks in the interior to balance the light surface rocks, and give the general average of $5\frac{1}{2}$. This alone suggests an iron core for the Earth, because iron has a suitable density of nearly 8.

The timing of earthquake waves opens another line of inquiry. When there is a discontinuity, a break between one kind of material and another, we are apt to get reflection at the break. By timing the waves down and up we find the depths at which discontinuities occur. Earthquake waves, like other waves, travel at different speeds through different materials. This complicates things, and makes the evidence difficult to interpret. But it is not impossible.

Meteorites provide a third line of inquiry. They are reasonably taken to be fragments of an exploded planet. Perhaps the most interesting thing about them is that chemically there is nothing startling in them. They might very well be fragments of the Earth itself, but fragments taken from different parts of the Earth, some from near the surface, and some from deep down in the interior. For there are two different kinds of meteorite. Iron meteorites consist chiefly of iron, nickel, and cobalt. The much lighter, stony meteorites consist largely of silicates. Meteorites give us, apparently, samples of

planetary substance at different levels beneath the surface of the planet.

A fourth line of inquiry lies in the examination of what happens in a blast furnace where there is some sort of likeness to earthly conditions. We notice to begin with that a furnace contains mixed materials above, siliceous slag below, and molten iron below the slag. We must not, of course, take the parallel between furnace and Earth too far, but we do get some help from it.

By piecing together evidence from many sources in this way, we arrive at a picture of the earth's interior:

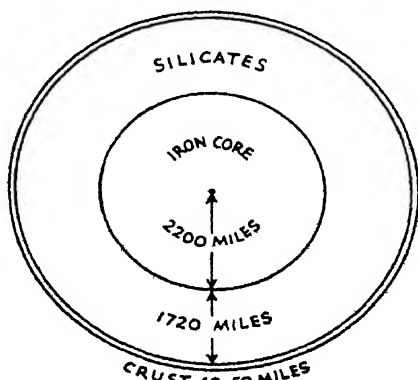


FIG. 20

(i) A hard, heavy, core of iron and nickel, with a radius of 2,200 miles.

(ii) Round this core a mantle of silicates, resembling olivine, which is a silicate of magnesium and iron. The thickness is 1,720 miles.

(iii) An outer crust of lighter rocks, 40 or 50 miles thick. The crust is itself differentiated. At the surface there are acid granitic rocks, heavier basic rocks below, and

intermediate rocks between. We get lighter rocks near the surface, and heavier and heavier rocks as we go down. The crust is greatly contorted, so that the three groups of rocks occur in different orders, and all three come to the surface in various places. There is ample evidence, however, that normally acid rocks are above, and basic rocks below.

The problem arises: how did this arrangement come about? The comparison with a blast furnace suggests an answer. At the time of the earth's formation, pressure at the centre would have raised the temperature to a great height. In these conditions molten iron would have fallen

through the silicates to the centre, and the lightest rocks would have been pushed to the surface.

Little Hydrogen less Helium

With such a superabundance of hydrogen and helium in the universe as a whole, it may seem a little odd that there should be comparatively little of these gases in the Earth. Most of the Earth's hydrogen is combined with oxygen to form the water of the oceans. And this hydrogen forms only an 80,000th part of the whole mass of the Earth. A vast mass when it is expressed in tons, but an insignificant fraction when compared with the two-thirds proportion of the universe as a whole. As for helium, it is something of a rarity in the Earth.

The reason given for the wide difference between the chemical composition of the Earth and that of the universe as a whole, is this. During the period of the Earth's formation, the rocky core of the Earth was too small to attract the lightest gases, and so these gases never did form a large part of the Earth's substance. When the Earth's surface was hot the lightest gases were lost to space. But hydrogen would be retained in the heavier molecules of water in the Earth's crust.

Jupiter, on the other hand, had a rocky core which seems to have been six times as heavy as that of the Earth. This was heavy enough to attract hydrogen and helium, and these gases now form the greater part of the mass of Jupiter.

How our Atmosphere was Formed

A peculiarity of the atmospheres, not only of the Earth, but of all the inner, and smaller planets, is the almost complete absence of free hydrogen and helium. These gases were not attracted to the smaller planets, and any amounts of them that were present would be lost to space. Evidence points to the fact that the earth's atmosphere was formed after the solid crust. We have to consider, therefore, how the various gases got into the atmosphere.

Igneous rocks and meteorites contain a large amount of gas, which is given up when they are heated to redness.

The volume of gas from some meteorites has been found to be as much as fifty times that of the heated rock.

Nitrogen is almost certainly of volcanic origin, that is, it comes from heated rock. Volcanoes do pour out free nitrogen. They also pour out ammonia, and this may be oxidized to nitrogen and water.

Carbon dioxide is another volcanic product. Usually it comes second to water in quantity, and in the later stages of volcanic activity the products are almost entirely water and carbon dioxide. Carbon dioxide is also liberated by shellfish. Rivers carry calcium bicarbonate in solution. Shellfish use the carbonate for their shells, and release the extra carbon dioxide; some of this reaches the atmosphere. But this source of carbon dioxide is merely a replacement of the gas already washed out of the atmosphere by rain. In the last fifty years a quite considerable addition has been made to atmospheric carbon dioxide by the burning of large quantities of coal, and by extensive fermentation. We are still, however, largely dependent on volcanic activity for maintaining the supply of atmospheric carbon dioxide.

Free Oxygen

There is no satisfactory evidence that free oxygen exists anywhere outside the earth's atmosphere. There may be traces of it elsewhere, but there is no conclusive evidence of this. As far as we know, the Earth's atmosphere is unique.

The first supply of oxygen probably arose from photo-dissociation in the upper layers of the atmosphere, that is, the breaking up of molecules under the influence of light. Water would thus yield free oxygen, and the much lighter hydrogen. The hydrogen would be lost to space, and the oxygen would be slowly carried down by convection currents.

The first green plants would thus have had the small amount of oxygen that they needed. They would have added to the supply by the photosynthesis of starch, in which process free oxygen is released. It is now commonly

held that photosynthesis is the chief source of our supply of free oxygen.

Water and Life

Apart from sheer quantity there seems to be little difficulty about the presence of water. Enormous quantities are poured out by volcanoes, so it appears that it came from the solid earth. The great quantities of water can thus only be explained if we accept the idea that the atmosphere came after the solid crust; no other reasonable explanation has been offered.

The first plants on earth would have had water and carbon dioxide, two of the necessities of life. Photodissociation would have provided a small amount of free oxygen. The rocks would have provided mineral salts. The remaining requirement is fixed nitrogen, that is, nitrogen united with other elements.

Nitric oxide has been detected in the atmosphere. It is produced when nitrogen and oxygen are synthesized by lightning flashes. There is never much of the gas in the atmosphere, because it is washed down by rain as nitric acid. The nitric acid forms nitrates in the soil, and these can be used by plants.

Why so Much Argon?

All but the veriest traces of most of the inert gases have vanished from the Earth's atmosphere. Apparently their inertness was their undoing. They did not combine with other elements, and only small amounts were held in the rocks. They were lost to space before the earth's crust had cooled sufficiently for an atmosphere to be retained.

The one exception is argon, which forms about 1 per cent of the atmosphere by volume. Why so much argon? The answer seems to be that argon, like the rest of the atmosphere, came later. And from a rather extraordinary source.

K^{40} , one of the isotopes of potassium, is radioactive, and the A^{40} isotope of argon is a product of its decay.

The large amount of argon in the atmosphere appears to have come from this source. The evidence is:

- (i) K^{40} does decay to A^{40} .
- (ii) An excess of A^{40} is found in potassium minerals.
- (iii) The isotope A^{40} forms about 99.6 per cent of atmospheric argon.

The evidence for the later production of atmospheric argon in this way appears to be satisfactory.

The Inner Planets

The densities of the inner planets tell us something about their chemistry. They are:

Mercury	.	.	.	.	.	2.86
Venus	.	.	.	.	.	4.86
Earth	.	.	.	.	.	5.52
Mars	.	.	.	.	.	3.84
(Moon	.	.	.	.	.	3.33)

The fairly close densities of the Earth and Venus suggest a similar composition, with less of the heavy iron core in Venus. Mars must have a still smaller heavy core.

The density of granite is between $2\frac{1}{2}$ and 3, and that is just about the density of Mercury. That planet may very well be composed chiefly of silicates. The moon also probably contains large quantities of silicates. Its density is higher than that of the Earth's crust, and this seems to be an argument against the idea, sometimes put forward, that it was torn away from the part of the Earth now covered by the Pacific Ocean.

Airless Mercury

Mercury is singular. It is the planet nearest to the sun, and it revolves round it with one side always turned towards the sun and the other side facing the chill of space. One side is perpetually very hot, and the other side perpetually very cold.

If there is any atmosphere on Mercury it must be tenuous in the extreme. The temperature is so low on the

cold side of Mercury that the atmosphere would freeze. Any atmosphere on the hot side would then flow to the cold side, to be frozen in its turn. In this way we should rapidly reach an airless condition.

It has been suggested that there may be traces of argon on Mercury, and possibly also krypton and xenon; but these are rather guesses at possibilities than established facts. If these gases do exist on Mercury they must do so in extremely small quantities.

Carbon Dioxide on Venus

Venus is our sister planet. It is nearer to us than any of the other planets. It is about the same size as the Earth, and its density is not very much less than ours. Venus is far and away the brightest of all stars. Indeed, its very brightness makes it difficult to observe, because the brightness comes from light that is reflected from a cloud-laden atmosphere.

There seems to be no doubt at all that the atmosphere of Venus consists largely of carbon dioxide. Very probably there is nitrogen in the atmosphere, but nitrogen is difficult to observe, so we cannot be sure. It is also quite probable that argon has been set free in the same way as it has on the Earth, by the radioactive decay of K^{40} . Probability is lent to these conjectures by the nearness and similarity of the two planets, and the fact that we expect similar conditions to give rise to similar chemistry.

But there are some things lacking in the atmosphere of Venus. No free oxygen has been detected there, and no water. Plant life requires, before anything else, water. And if plant life did exist on Venus it would probably release oxygen by the process of photosynthesis. Evidently there can be no plant life on Venus. And if there is no plant life, there can be no animal life.

The clouds that shroud Venus so effectively are yellow in colour. They cannot be water clouds, which would be white. They are probably 'siliceous material tinted with iron'—like the sands of the sea-shore. There seems to be

very great turbulence in the atmosphere of Venus, sufficient to cause perpetual dust storms. Such storms would account for the clouds of dust that obscure the planet.

If Venus had a good supply of water, its atmosphere might become rather like our own. Photodissociation of water would provide at least a little free oxygen. But Venus is an arid spot, quite unlike our own planet.

Lichens on Mars?

Mars has attracted much attention from scientists because it is comparatively near, and it is not obscured by clouds as Venus is. Novelists also have woven romances about life on Mars, but their tales are usually far removed from the probable dismal reality.

The rather low density of Mars suggests, as we have noted, that it probably has a much smaller iron core than the Earth. It would be even less effective than the earth in capturing and holding an atmosphere of hydrogen and helium. And yet it has an atmosphere that can be clearly observed, although it is rather thin. It seems to have about a twenty-fifth of the density of the Earth's atmosphere.

Carbon dioxide has definitely been detected in the atmosphere of Mars, and it probably forms a greater proportion of that atmosphere than it does of our own. Nitrogen probably exists in the Martian atmosphere, but as usual it is difficult to detect. And there is probably some argon.

There is good evidence for the existence of some water on Mars, though the quantity is small, and not to be compared with our deep oceans. There are white caps about the poles and these have been identified with some certainty as water. It was thought at one time that they might be frozen carbon dioxide, but this idea had to be given up. Mars is certainly cold, but not cold enough to freeze carbon dioxide in the very low pressure of the Martian atmosphere. The proportion of water vapour in that atmosphere has been estimated as $\frac{1}{200}$ of that in the Earth's atmosphere.

There are clouds in the Martian atmosphere, but they

are not like the dense, obscuring clouds of Venus. It is possible to have a good view of the planet's surface. There are large, reddish parts of the surface which are commonly called 'deserts'. These regions are probably covered with igneous rocks, and the red tint may be due to iron.

About a third of the surface of Mars is coloured green. These parts are the most exciting, because they undergo seasonal changes. In some parts there are areas which are clearly green in the Martian midsummer. Then the green turns to brown, and the brown to yellow. These seasonal changes suggest those that occur in plants in our temperate zone.

Mars has water and carbon dioxide, two of the essentials of life. It probably also has nitrogen, and the various minerals that plants need. But free oxygen has not been detected.

Though most of the necessities for life are present on Mars there does not seem much possibility of life there. Conditions are very rigorous. The temperature is extremely low; the most that could be expected in the way of liquid water would be melting ice. There is an excessively long winter. The Martian year is about twice as long as our year; it is 687 days. So the winter must approach one of our years in length. The absence of free oxygen adds to the rigour of the conditions. Professor Kuiper, in *The Atmosphere of the Earth and Planets* suggests that the only group of plants which might survive such onerous conditions is the lichens. Lichens have been dipped in liquid air, down to -190°C. , and have continued to live. The absence of free oxygen does not kill them. Another point is that they do not send free oxygen into the air; so the absence of free oxygen on Mars does not rule out the possibility of lichen life.

There are, however, difficulties about accepting the idea of lichens on Mars. Lichens are an example of symbiosis, the partnership of two forms of life. They are a symbiosis of fungi and algae. How that partnership arose, and why it should arise in two planets, needs some explanation. Since most theories of the origin of life contain the word

'chance'—the chance production of this or the chance production of that—it does seem odd that the same outrageously improbable chance should occur on both planets. If, however, there is any life on any other planet, the only possibility seems to be lichens on Mars.

Mighty Jupiter

The major planets, Jupiter, Saturn, Uranus, and Neptune, are very different from the inner, and minor, planets. This is chiefly because of their much greater size. Mighty Jupiter has 318 times the mass of the Earth, Saturn 95 times, Uranus 15 times, and Neptune 17 times. In the period of planet formation the major planets were big enough to attract, and consolidate into themselves, hydrogen and helium.

A probable description of the structure of Jupiter is:

A rocky core, about six times the mass of the Earth. This forms one-fiftieth of the mass of Jupiter. Round the rocky core are layers of frozen water, methane, and ammonia. Rocky core and frozen layers together make up two-tenths of the planet. The rest of Jupiter is chiefly a highly compressed mixture of hydrogen and helium. These two gases make up eight-tenths of the planet.

There is certainly ammonia in the atmosphere of Jupiter. The heavy clouds in the atmosphere are made up of crystals of solid ammonia. The colours of the clouds may be caused by solutions of sodium in liquid or solid ammonia. There is also much methane.

There are at least three conditions that make life impossible on Jupiter. Because of its vast size materials would weigh nearly three times as much as they do on the Earth; the atmosphere does not contain the materials necessary to life—it would in fact poison life; and the temperature is extremely low. We should look in vain for the beginnings of life on Jupiter.

The Jovian Planets

Saturn, Uranus, and Neptune are classed with Jupiter, because of their great sizes.

Saturn has an atmosphere similar to that of Jupiter,

but with less ammonia. The rings which surround Saturn are very bright; they are probably covered with snow. The five satellites also have bright reflecting surfaces; they are at least covered with snow, and they have been described as gigantic snowballs.

Uranus and Neptune have low densities, only about a quarter of that of the Earth. The cores of these planets are probably not iron, but the much lighter silicates. The atmospheres contain hydrogen, helium, and a considerable amount of methane.

When space-ships really get going, and the first adventurers land on other planets, I cannot help thinking that they will have a poor sort of welcome from our neighbours in the solar system. They may well desire a quick return to our not uncongenial Earth.

SOME CHEMICAL TERMS

It may be convenient to be reminded of the meanings of some chemical terms. Some of them are more fully explained in the text.

activate. To make a substance temporarily radioactive, by bombarding it, usually with neutrons. Only a comparatively few of the atoms actually become radioactive.

adsorption. The adhesion of a very thin layer of a gas or liquid to the surface of a solid. Such layers are usually only one molecule thick.

alpha-particles. Positively charged particles consisting of 2 protons and 2 neutrons. They are helium nuclei.

anion. See *ion*.

atom. The smallest particle of an element that is the element.

atomic number. The elements are numbered 1 to 101. The atomic number refers to the number of protons in the nucleus of an atom of the element.

carrier. When a trace of an element is being recovered, a larger quantity of a similar element may be added as a carrier. Owing to chemical similarity the two elements may be brought down together as similar compounds. They may then be separated.

catalyst. A substance which assists a chemical reaction without itself taking part in it. The catalyst is unchanged.

cation. See *ion*.

centrifuge. A machine for separating materials by rotation. Liquid may thus be flung out through a fine mesh, whilst solids are retained.

chromatography. A means of chemical analysis in which a weak solution runs down in blotting paper. Materials in solution separate along the blot.

colloid. Very finely divided matter. A colloid will pass through a filter paper, but not through parchment paper.

- compound.** A substance formed by the chemical union of two or more elements.
- convection.** Motion in a liquid or gas caused by differences in density. Convection currents in air or water are often caused by one part being heated or cooled.
- density.** The weight of a substance per unit volume: pounds per cubic foot, grams per cubic centimetre. When given simply as a number it is the weight compared with the weight of an equal volume of water: this is specific gravity.
- deuterium.** Heavy hydrogen. It is nearly twice as heavy as ordinary hydrogen.
- diffusion.** The spread of one substance into another, *e.g.* the spread of escaping gas into the surrounding air.
- electron.** A minute particle with a negative charge. It has extremely small mass.
- element.** A substance which consists of one material only, and from which no other material can be obtained. Iron is an element, because it is iron and nothing else. Carbon dioxide is not an element because it can be split into carbon and oxygen.
- fission.** The breaking of atoms into parts of not greatly unequal size.
- fractional distillation.** Separating substances with different boiling points, by heating the mixture to a temperature at which the substance with lowest boiling point boils off. The process may be carried out in several stages, with rising temperatures.
- gamma-rays.** Electromagnetic waves of very short wavelength.
- hydroxyl.** The group OH which occurs in water, alcohol, and other liquids.
- ion.** A charged particle, either an atom or a group of atoms. **Cations** have positive charges. **Anions** have negative charges.
- isotope.** Most elements have more than one kind of atom. The different species of an element are called isotopes. The isotopes are chemically alike but have different masses.

molecule. The smallest part of a compound that is that compound. A molecule is formed by the union of two or more atoms. Thus, the molecule of salt-petre, KNO_3 , consists of one atom of potassium united to one atom of nitrogen and three atoms of oxygen.

neutron. A minute particle with no electric charge. It has about the same mass as a proton.

nucleus. The extremely minute particle at the centre of an atom. It consists of protons and neutrons.

oxidize. To cause union with oxygen, by supplying the gas, or some suitable substance containing oxygen.

photosynthesis. See *synthesis*.

precipitate. A substance formed in small insoluble particles when one liquid reacts with another.

saturate. To dissolve as much as possible of a solid in a liquid. A **supersaturated** liquid contains more of the solid than is normally required to saturate it.

sol. A colloidal solution, that is, a colloid forming a permanent suspension in a liquid.

spectrum. The range of rainbow colours formed when light passes through a prism. Lines on the spectrum are used as a means of analysis.

sublime. To change directly from solid to gas, or from gas to solid, without the intermediate liquid state.

suspension. Fine powder held in a liquid without being dissolved in it.

synthesis. Putting together atoms to form molecules, or simpler molecules to form more elaborate ones. In **photosynthesis** the synthesis proceeds under the influence of light.

tracer chemistry. The use of activated material in chemistry. The easily-detected radioactive atoms show what happens to the bulk of the material.

transuranium elements. Elements which have atomic numbers higher than that of uranium, 92. Nine of these elements are now known, 93 to 101.

